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PAPERS

FOREWORD

This is the first TRANSACTIONS volume published by the Institute containing only papers on mining geology. It is made up of papers that have appeared during the past three years as TECHNICAL PUBLICATIONS or CONTRIBUTIONS, with two that have not been printed before.

Several papers dealing with the broader geologic principles of ore occurrences, particularly with the structural and tectonic setting of ore deposits, are contained in the first part of the volume; but the greater part deals with detailed and local descriptions of individual mineral deposits of various types, including typical deposits of complex ores, iron ores and certain of the nonmetallics. Many of the papers are the product of original field and laboratory work in districts on which little heretofore has been published. The symposium at the end of the book thoroughly discusses the relationship of Government surveys to the mining industry.

With the publication of this volume preparation must begin for future volumes, to be published when suitable papers have been selected. Mining geology in particular is a progressive study and we must look to the future for the solution of many of its most significant problems. Nearly all of the important ore discoveries of the past can be attributed to surface manifestations overlying the deposits. In the future greater skill will be necessary in order to find ore deposits that give little or no surface indication of their presence. To gain this end renewed efforts must be made to better understand the relationship of physical-chemical processes to ore deposition and to other mineralization, and to interpret the findings of the geophysicists in terms of economic results. In these fields lie ample opportunities for exercise of the utmost skill and intelligence of the young geologists who now sometimes may be inclined to wonder whether or not there is anything left for them to do. They can be assured that in the interpretation of the geology of the many areas that remain to be studied, or that in the past have been mapped merely as "complex" or "confused ground," there are abundant opportunities for the resourceful geologic observer to prove that such problems will yield to persistent and painstaking study, provided the geologist overcomes his own initial confusion. Suitable papers for future volumes are earnestly requested by the Committee on Mining Geology.

GEORGE M. FOWLER, *Chairman*,
Committee on Mining Geology.

JOPLIN, MISSOURI
June 18, 1935

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On the Origin of Certain Systems of Ore-bearing Fractures

By W. H. Emmons,* Member A.I.M.E.

(New York Meeting, February, 1935)

In 1922 Morey made a series of experiments in which he observed the cooling of a molten system containing H_2O, 9.1 per cent; K_2O, 17.3 per cent and SiO_2, 73.6 per cent. This system was confined in a bomb; it was fluid at 500° C. and exerted no vapor pressure. In cooling to 420° C. a large part of it crystallized and at that temperature much of the water had separated from the crystals and remained as steam, which built up a pressure of 4998 lb. per sq. in., a force sufficient to lift nearly one mile of granite.[1]

If granite, cooling at 600°, expels vapor in the process of crystallization it is reasonable to suppose that a considerably greater vapor pressure would result, and it is thought that the vapor expelled from crystallizing granitic batholiths probably has a pressure sufficient to lift two or three miles of granite. This vapor, collecting near the tops of cupolas of batholiths, is believed to exert sufficient pressure to fracture the hoods and roofs of batholiths above the cupolas. If that is true, one would expect to find that the fracture systems above cupolas are arranged in patterns that depend in part on the shapes of the cupolas.

The mechanics of the situation seem to require that conical cupolas should have radial fracture patterns, that bluntly rounded cupolas should have fracture systems that are either irregular or rudely conjugated in plan, and that elongated stocks or cupolas should have fracture systems in which the fractures lie nearly parallel to the direction of the elongation of the cupolas.

Study of essentially all the cupolas of the earth that have associated important vein-filled fractures shows that this is generally true. This

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Manuscript received at the office of the Institute March 15, 1934.

* Professor of Geology, University of Minnesota; Director of Minnesota Geological Survey, Minneapolis, Minn.

[1] G. H. Morey: Development of Pressures in Magmas as a Result of Crystallization. *Jnl.* Wash. Acad. Sci. (1922) **12**, 219–310.

P. Niggli: Ore Deposits of Magmatic Origin. Trans. by H. C. Boydell, 1–93. London, 1929.

W. H. Emmons: On the Mechanism of the Deposition of Certain Metalliferous Lode Systems Associated with Granitic Batholiths. Ore Deposits of the Western States (Lindgren Volume), 327–349. New York, 1933. A.I.M.E. The pressure of gas released by cooling granite is discussed on page 339 of this paper.

very common relation seems to support the theory that such fracture systems may owe their origin to the vapor pressure that is generated by the volatile fluids expelled from cooling and crystallizing granitic batholiths.

Batholiths

Metalliferous lodes that are eroded so deeply that they reveal the patterns of batholiths and cupolas[2] generally show close space relations between the lodes and the intrusive igneous rocks. The conclusion that there is a genetic relation between them is inevitable. It does not follow that all lode deposits have formed in connection with these intrusives, but probably the majority of them have so formed. The general problem is not discussed in this paper, which takes up only a special phase of it, but in order to clarify the discussion, certain broad features of the subject should be stated.

The batholith rises into the region of emplacement by fluxing, stoping and thrusting its way up. The composition of the magma is probably intermediate or basic, but it becomes granitic by differentiation. The border phase is chilled and solidified at an early stage because it is nearest the surface and because around high points there are larger cooling contact areas. This phase commonly is more basic than the interior or central portions of the batholith because it solidified before differentiation and small projections of the intrusive extend upward into the roof. The batholith generally broadens downward (Fig. 1).

Dead Line and Hood.—It is established that the interiors of large granitic batholiths are barren of important deposits of the metals. The dead line is the line, or rather the warped plane, below which valuable deposits are essentially wanting. It resembles the contour of the top of the batholith, but its contour is less accentuated. The hood of the batholith is the part that lies between the roof and the dead line; it is the part of the batholith that contains valuable ore deposits. It is about three miles thick at the tops of high cupolas and about one mile thick at the troughs between them.[3] The core is essentially barren.[4]

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[2] G. Steinmann: Ueber gebundene Erzgänge in der Kordillere Südamerikas. Int. Kongr. Düsseldorf, 1910. Abt. IV, Vortrag 20, 172–181.

J. T. Singewald, Jr.: The Erzgebirge Tin Deposits. *Econ. Geol.* (1910) **5**, 166–177, 265–272.

H. G. Ferguson and A. M. Bateman: Geologic Features of Tin Deposits. *Econ. Geol.* (1915) **10**, 209–262.

B. S. Butler: Relations of Ore Deposits to Different Types of Intrusive Bodies in Utah. *Econ. Geol.* (1915) **10**, 101–122.

[3] This is a maximum; many hoods are only a few hundred feet thick.

[4] This statement is based on sound statistical data. In connection with studies of mineral zoning, essentially all of the valuable deposits of the earth have been plotted by myself and assistants. Even small unprofitable deposits that have produced a little ore are practically absent from the cores of batholiths except in and near roof pendants.

Stocks and Cupolas

According to Grout,[5] stocks seem to be essentially small batholiths not more than about 20 square miles in area, or cupolas rising above the general level of the batholith roof. Most students of petrology use the term essentially as Grout defines it, but as used by some, the stock is a broader term applied to any intrusion that is broader than the ordinary dike and not more than a few times as long as it is broad, and that does not lie with beds. Daly[6] defines the cupola as a body extending upward from the roof of a batholith. It is commonly implied that the cupolas broaden downward and probably that is true in general, although at the

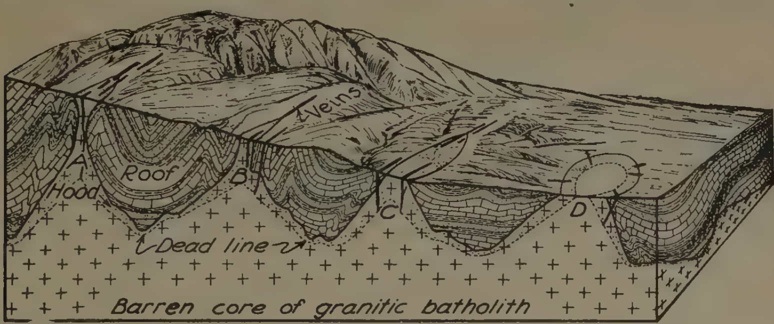

FIG. 1.—DIAGRAM OF REGION TRUNCATED ALONG INCLINED PLANE TO ILLUSTRATE BATHOLITH EXPOSED AT DIFFERENT ELEVATIONS.

A. Funnel-like intrusion (ethmolith), with elongated outcrop, rising from cupola; veins lie nearly parallel to long axis of its outcrop.

B. Wedgelike intrusion (sphenolith) rising from cupola; veins in and near wedge strike approximately in direction of long axis of outcrop.

C. Cupola with veins in and near it striking approximately parallel to long axis as shown in plan.

D. Conical stock with circular plan and veins in hood and roof that radiate from core.

depths within the zone of observation some stocks have vertical walls or even walls that slope inward. Stocks with walls that are nearly vertical or that are wedgelike are "sphenoliths," and stocks that contract with depth are "ethmoliths." Both of these types are believed to be upward extensions of batholiths and both types may be underlain by cupolas or upward swells that broaden downward.

Epigenetic mineral deposits are greatly concentrated around stocks and cupolas; in general the sulfide ores of contact-metamorphic origin are found around small stocks. Valuable deposits of this group are rarely, if ever, found around stocks that are more than 5 miles in diameter.

Illustrations of various types of stocks and of other upward swellings of the hoods of batholiths are shown on Figs. 1 and 2. Five of these

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[5] F. F. Grout: Petrography and Petrology, 35. 1932.

[6] R. A. Daly: Igneous Rocks and Their Origin. New York, 1914. McGraw-Hill Book Co.

show elongated outcrops of intrusives; one is circular. In Fig. 1, at *A* is shown an ethmolith rising from a normal cupola. This figure shows a structure something like one that would be outlined by the frame of a greatly elongated sawbuck. In the examples that are available the parts that lie below the necks are not developed; but since the roofs of batholiths generally slope outward from the stocks it is inferred that the funnel-like body in depth will generally broaden. *B* shows a sphenolith rising from a cupola, *C* illustrates the normal cupola with definite elongation, and *D* shows a batholith at a deeper stage of erosion. In Fig. 2, *A* is the normal cupola like *C* in Fig. 1. *B*, Fig. 2, is a larger body of which the interior is barren, but on the right side there is a marginal roof

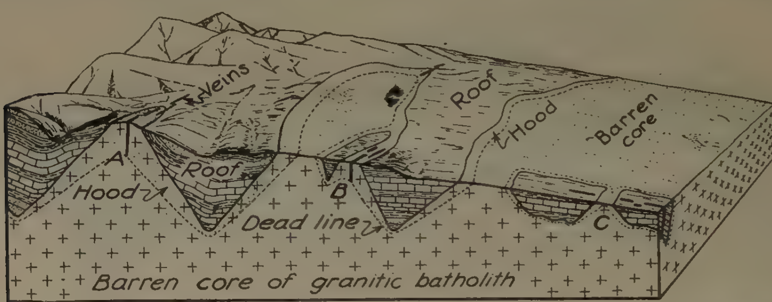

FIG. 2.—DIAGRAM OF REGION TRUNCATED ALONG INCLINED PLANE TO ILLUSTRATE BATHOLITH EXPOSED AT DIFFERENT ELEVATIONS.

Metalliferous deposits are in hood and in roof; core is barren. Concentrations are in and near: (*A*) cupola, (*B*) border pendant, (*C*) hourglass structure.

A. High cupola; veins lie in and near it and are approximately parallel to long axis of outcrop.

B. Border roof pendant; veins lie in granite between it and border.

C. Veins developed on hourglass structure with neck of granite that lies between roof pendants. Veins lie in and near neck of hourglass, but many strike across it. All these deposits lie in or near upward bulges of hood.

pendant. Lodes are found in the granite between the roof pendants and the contact of the granite with the main body of the invaded rock. The lode system is the roof-pendant border-zone type. This body has also a vein in a "finger." At *C*, Fig. 2, a large apophysis of the granite cuts across roof pendants, making what is called the "hourglass" structure. Lodes are deposited in and near the neck of the "hourglass."

Each of the six types described probably is an expression of a similar feature; namely, an upward swell of the batholith. Stocks as at *A* and *B*, Fig. 1, with deeper erosion will probably be shown to join cupolas, and features like *B* and *C* of Fig. 2 would have shown either cupolas or narrow fingers before erosion had gone so deep. At *D*, Fig. 1, the lodes are radially disposed about the outcrop of the intrusion. In all other figures the lodes are shown to lie rudely parallel to the long axis of the stock except at *C* in Fig. 2, where the lodes lie near the hourglass neck but strike parallel to the contact of the main granite mass and the

invaded rocks. Figs. 1 and 2 were drawn after essentially all mapped cupolas and their deposits were compared. *A* in Fig. 2 illustrates more than 200 examples; *B* is not a rare type, and the other types are represented in two or more districts.

Rise of Gases

There are few quantitative data concerning the amount of water in magmas and the results obtained by a consideration of these data are of qualitative value. The relations established by Goranson's[7] experiments seem to show that the water of the earth is very greatly concentrated in the outer 60 km. of the earth's shell.[8] The observations of Fenner, Zies, Allen, Day and associates,[9] and other observations presented by Fenner seem to justify the conclusion that large amounts of water and other volatile substances are present in certain magmas. This seems also to be the view of Sapper.[10] Few quantitative estimates are available; A. L. Day[11] states that silicates in the magma contain several per cent of water. Bowen,[12] on the other hand, believes that the water content of most magmas is relatively small.

Large volumes of water and of chlorine and of fluorine are known to pass from volcanic centers.[13] In some eruptions these quantities are enormous. Zies estimated that fumaroles of the Valley of Ten Thousand Smokes involved 1,250,000 tons of hydrochloric acid and 200,000 tons of hydrofluoric acid annually and Calkins[14] calculated from the amount

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[7] R. W. Goranson: The Solubility of Water in Granite Magma. *Amer. Jnl. Sci.* (1932) [5] **22**, 481–502.

[8] W. H. Emmons: The Basal Regions of Granitic Batholiths. *Jnl. Geol.* (1933) **41**, 1–11.

[9] C. N. Fenner: The Katmai Region, Alaska, and the Great Eruption of 1912. *Jnl. Geol.* (1920) **24**, 602.

E. G. Zies: The Valley of Ten Thousand Smokes. Nat. Geol. Soc. *Contr. Tech.* (1929) **1**, 1–61.

E. T. Allen and E. G. Zies: A Chemical Study of the Fumarole of the Katmai Region. *Idem* (1923) **1**, 75–155.

C. N. Fenner: Pneumatolytic Processes in the Formation of Minerals and Ores. Ore Deposits of the Western States (Lindgren Volume), 58–106. New York, 1933. A.I.M.E.

[10] K. Sapper: Vulkankunde, 32–60. 1927.

[11] A. L. Day: Physics of the Earth, I. Vulcanology. *Bull.* 77 Nat. Res. Council (1931) 5.

[12] N. L. Bowen: The Broader Story of Magmatic Differentiation Briefly Told. Ore Deposits of the Western States (Lindgren Volume), 106–151. New York, 1933. A.I.M.E.

[13] C. N. Fenner: Second reference of footnote 9, 76.

J. B. Umpleby: Geology and Ore Deposits of the Mackay Region, Idaho. U. S. Geol. Survey *Prof. Paper* 97 (1917) 77.

[14] W. H. Emmons and F. C. Calkins: U. S. Geol. Survey *Prof. Paper* 78 (1913) 128.

of scapolite developed around the Philipsburg batholith that the chlorine given off was measurable in cubic miles at ordinary temperatures and pressures.

The conditions at Vulcano, Lipari Islands, are instructive. The crater of Vulcano has been in a state of solfataric activity since 1890 and since 1917 this activity has increased.[15] On the north wall of the crater, gases with a temperature of 600° C. issue from fumaroles, and halite, bismuthinite and tetradymite (bismuth telluride) are deposited. Sulfur springs issue in the alluvial area between the main crater and Vulcanello. These hot springs have deposited large bodies of FeS_2 below the ground-water table, partly as black amorphous masses, partly as crystalline pyrite, which cements the loose material to form solid beds. Above the ground-water level native sulfur is deposited as a cement. The surface is covered with crusts of sulfates, which include plant remains. The formation of pyrite was shown to take place as deep as 40 meters below sea level. At considerable distances from the crater, springs with CO_2 and iron compounds are found and these deposit limonite and siderite.

It is probable that certain magmas that rise toward the earth's surface are saturated with water and other volatile substances in solution. Pressure would decrease, owing to ascent, and decrease in pressure lowers the capacity of the magma to carry water in solution. Escape of gases could take place at this stage with contact metamorphism of the invaded rock. Probably certain ores of contact-metamorphic origin are formed at this early stage, but the chief period of ore deposition is later.

When crystallization of the magma begins, femic crystals, which in general have higher melting points, will form first. These sink, by gravity, and the lighter minerals, forming somewhat later, rise. There is not much concentration of water in these products, for basic rocks are about as high in water as acidic ones and some are higher. In a magma with 2 or 3 per cent of water, the water will be concentrated in the liquid remainder of the magma because most crystalline rocks—acidic and basic—carry less than 2 per cent water, the average being 1.15 per cent.

In the early stage of cooling of a batholith probably most of the water is held in solution. It is doubtful whether any steam bubbles would be present in any such magma,[16] for as the temperature of the magma is lowered its capacity to hold dissolved water is increased. At a pressure of 1000 bars[17] and a temperature of 900°, a granitic glass[18]

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[15] F. Bernauer: Rezente Bildung einer Kieslagerstatte auf der Insel Vulcano. *Ztsch.* deut. Geol. Ges. (1932) **84**, 568.

[16] K. Sapper: Reference of footnote 10, 56.

[17] About 987 atmospheres.

[18] R. W. Goranson: Reference of footnote 7.

may hold about 6 per cent water, and at about this pressure lowering the temperature 300° will increase the amount of water soluble in the magma nearly 1 per cent. At a greater pressure it will hold more water and at lower temperatures also it will hold more water. It is probable, therefore, that in a gastight container no steam would separate at the early stages of cooling that follow emplacement.

It is probable that bubbles of steam rising through a magma serve as vehicles by which metals are carried upward, for into these bubbles are distilled, from the surrounding magma, gases with lower vapor pressure. As pointed out by Fenner,[19] they act as vacua in relation to such gases and could serve as collection chambers for other gases.

If a magma moderately high in water had become 90 per cent crystalline, the residue or "rest magma" would contain a relatively high con-

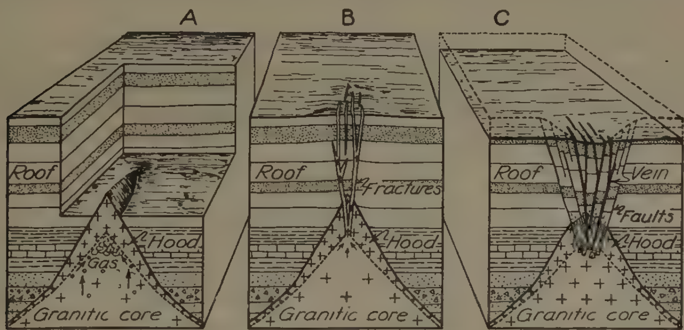

FIG. 3.—*A*. CUPOLA WITH GAS ACCUMULATION BELOW IT AT PINNACLE OF CORE. *B*. FRACTURES FORMED BY FAILURE OF HOOD AND ROOF ABOVE CORE PINNACLE. *C* GRABEN OR AREA OF SUBSIDENCE CAUSED BY ESCAPE OF GAS FROM PINNACLE OF CORE.

centration of water. Even though its capacity to hold water is increased by lowering of temperature and rising of pressure by crystallization of silicates, a point is reached where steam bubbles could form. These, gathering gases of lower vapor pressure, could rise by gravity. This probably is the chief stage of the final separation of metalliferous solutions from the magma of the batholith. The bubbles would rise to the base of the hood, pass to the pinnacles of the core and there form gas cones or cones highly charged with gas below cupolas of the batholith (Fig. 3*A*).

Room for the gas cones to form in a system already under pressure could be provided by the process of injection into the roof and hood of the batholith. Dikes formed at many stages are in evidence around most batholiths; the magmas send out apophyses during the period of emplacement and following it, even as late as the period subsequent to the deposition of metalliferous lodes.

When, as a result of crystallization, the vapor pressure is sufficient to fracture the cupolas and the parts of the roof near them, the fractures

[19] C. N. Fenner: Reference of footnote 13, 71–72.

will become the channelways that lead the gases to the hood or into the roof of the batholith. The fluid system, chiefly gas as it enters the fractures of the hood, becomes partly liquid as it passes upward and then chiefly liquid as it rises into the fractures in the upper parts of the hood and in the roof where fissures, permeable beds, easily replaceable beds, anticlinal structures, older faults, fractured pipes or subsidence pipes supply the channels that direct the solutions.

At the stage of separation of gas the magma consists of: (1) the rock-forming crystals, (2) the liquid "rest magma," and, (3) the volatile constituents. The magma may be a mush of crystals, or, as Umpleby suggests, a "sponge" of crystals "soaked with steam."[20]

Roots of Veins

Most students of metalliferous lodes who believe that lode ores are expressed from cooling igneous intrusives, probably have searched diligently at the bottoms of veins for connections with igneous rocks, but few veins in depth are known to pass into pegmatites or into any similar phase of igneous deposition that lies between the vein and the igneous rock. The writer searched for many years without success for such connections. In 1933 two veins in the Canadian shield were mapped and both showed rich gold-quartz tourmaline-ankerite filling. One of these veins is in a finger of a hood of a batholith and passes downward into a rubble-filled fissure that lies between walls that show very little hydrothermal alteration. The other vein is in the hood of a cupola and, where workable, follows a dike and passes downward into the barren fractured dike. It is reasonable to suppose that these veins that rose from barren fissures to become valuable lodes as they passed from core to hood, were deposited by solutions that separated from the magma as gases. The solutions may have become mixtures of liquids and gases before the ore was deposited, but if they had been derived by differentiation from a pegmatite or "aqueo-igneous" body one would expect them to pass downward into such a body.

It does not follow that all veins are deposited by solutions that left the magma as gases. The veins of Moonta in South Australia should be mentioned here. These copper veins are developed to considerable depths and in them feldspar becomes more prominent with depth and near the deepest levels feldspar crystals become much larger. The veins have strong pegmatitic affiliations and are classed as pegmatites by Jack.[21]

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[20] J. B. Umpleby: Reference of footnote 13.

[21] R. L. Jack: The Geology of Moonta and Wallaroo Mining Districts. South Australia Geol. Survey *Bull.* 6 (1917) 1–135.

The Zaaiplaats[22] tin pipes which rise into the top of the Bushveld granite mass branch upward as fingers. These also have strong pegmatitic affiliations, as have the gold lodes of Silver Peak, Nev., and the Yukon, as was pointed out long ago by Spurr.[23] It is possible that certain valuable lodes were deposited by solutions that separated from the magma first as pegmatite which on cooling supplied the fluids that deposited the lodes.

Explosion of Gas Cones at Core Pinnacles

It is highly probable as stated that gas accumulates at the pinnacles of the core that lie below the cupolas and that at such places gas cones form (Fig. 3). These may be gas or they may be portions of the magma of the core that are highly charged with gas. When the pressure of the gas is sufficient to fracture the hood and roof or to reopen older lines of weakness the gas may escape at first with explosive violence or, if openings are provided, it may issue more quietly. Passing upward it liquefies in part and deposits ores.

Relation of Lode Plans to Intrusives

If gas under high pressure accumulates at the high points of the undulating top of the batholith, this pressure would be exerted in all directions but it would tend to open the areas above the cupolas of the batholith because in these the roof of the batholith is thinnest. If the cupola is a regular cone and pressures were exerted against its walls in all directions, radial cracks should form, provided load and strength of overlying rocks were equal. Such systems of metallized fractures radiating from a granitic cupola are very rare. Fissures are disposed radially around the Lands End massive of southwest England,[24] and around the Arbus mass, Sardinia,[25] where veins in and near the granite stock form a rudely radiating pattern. These are the only districts where veins radiate from a circular granite mass. At Cripple Creek,[26]

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[22] R. A. Wagner: Handbuch der Regionalen Geologie. The Union of South Africa, 196.

[23] J. E. Spurr: Ore Deposits of the Silver Peak Quadrangle, Nevada. U. S. Geol. Survey *Prof. Paper* 55 (1906) 59.

J. E. Spurr: Geology of the Yukon Gold District. U. S. Geol. Survey 18th Ann. Rept. (1896) part III, 297–313.

[24] C. Reid, J. S. Flett and D. A. Macalister: The Geology of the Lands End District. *Mem.* Geol. Survey England and Wales; Explanation of sheets 351–358.

[25] G. Zoppi: Descrizione Geologico-mineraria dell' Iglesienle Sardegna. Min. descr della Carta geol d'Ilal (1888) 4.

[26] W. Lindgren and F. L. Ransome: Geology and Gold Deposits of Cripple Creek District, Colorado. U. S. Geol. Survey *Prof. Paper* 54 (1906) 1–516.

Colo., veins radiate from a volcanic center and volcanic pipes walled with ore are found at Braden mine, Rangagua,[27] Chile and at Verespatak[28] in Siebenbürgen, Transylvania. These deposits, however, form rims of volcanic bodies and do not radiate from them. The "perforation pipes" of Transylvania are mineralized by gold ores deposited in the brecciated contents of the denuded volcanic vents, as at Szevregyel Mountain, and at Csetatye Mountain.

When Daubrée made the classic experiment in which he deformed a cube of stone by compressing it and obtained on each free face two sets of

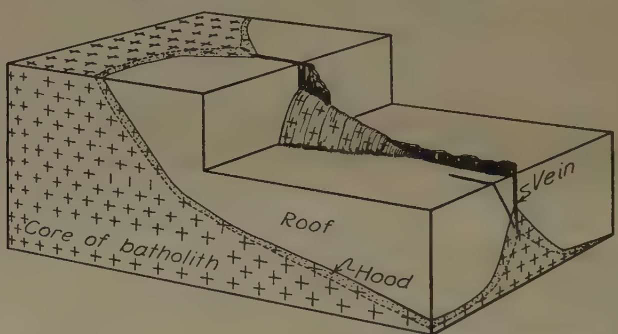

Fig. 4.—Fingerlike projection of batholith with vein striking parallel to long axis of projection.

fractures nearly at right angles to each other, it was inferred that fractures of mining districts showing such patterns either in plan or in cross-section had been deformed by compressive stresses. Conjugate patterns as viewed in plan are shown by a few mining centers in Cornwall and by the vein systems of Joachimsthal and of Schneeberg in the Erzgebirge, Saxony, and in Mount Chicote and Colcha districts, Bolivia. A small group of veins in Needle Mountains, Colorado, exhibit a conjugate pattern, as do also the Bonanza[29] mine in Zacatecas and a system of deposits in Zimapan,[30] Hidalgo, Mexico. The list of districts showing in plan, clean cut conjugate systems, however, is not a particularly impressive one when compared to the list showing parallel fractures with very little or no evidence of conjugation of the vein plans. Conjugated fracture systems probably may form at the blunt gently undulating tops of upward protuberances of batholiths, but the origin of some of these fracture systems is not clear.

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[27] W. Lindgren and E. S. Bastin: *Econ. Geol.* (1920) **17,** 75–90.

[28] M. von Palfy: Geologische Verhaltnisse und Erzgange der Bergbaue des Siebengeberge Erzgebirges. *Mett Yahrb.* d. Ungar. Geol. Reichsanstalt (1912) **18,** 230–526.

[29] J. E. Spurr: The Ore Magmas, 627. New York, 1923.

[30] *Idem,* 728.

The systems of rudely parallel veins are more common than all other vein systems combined. Some such systems are not connected with exposed igneous intrusives, but a very large number of them are. Most stocklike intrusives are distinctly elongated and many of the larger intrusives have fingerlike projections extending outward from them. Veins associated with the small elongated stocks and cupolas generally lie nearly parallel to the long axes of the stocks, and veins in and near the fingerlike projection of the larger bodies generally lie parallel to the long axis of the finger (Fig. 4).

The finger of acidic igneous rock commonly points to the deposit or else the deposit commonly lies in and is nearly parallel to the long axis of the finger. Some of these fingers are known to have sloping roofs and the axis of a finger commonly pitches outward from the main body of the batholith (Fig. 4). The finger in a certain sense is a cupola that extends outward and upward from the side rather than from the top of the batholith. As stated, the associated lodes as a rule strike rudely parallel to the axis of the finger. The relation is such as would be expected if fracturing were caused by pressure originating in the magma of the batholith, this pressure being exerted below the two walls of the finger that slope away from its axis. Likewise a cupola which resembles in shape the top of a hay rick would be fractured on lines nearly parallel to the roof of the cupola by pressure exerted from below on the sloping roof.

Thrust of the Magma

While the systematized relations of intrusive forms and the orientation of associated vein systems suggest that the latter have resulted from the vapor pressure built up in cooling intrusives, the intrusive thrust of the magma itself may be a possible agent of fracturing. This appears to be a reasonable explanation for fracture systems filled by dikes that radiate from a center of intrusion or that lie parallel to elongated stocks. Among the best known systems of radial dikes are those of the Highwood Mountains,[31] Montana, and Spanish Peaks,[32] Colorado. Dike systems parallel to elongated stocks or to fingerlike projections of batholiths are represented at Kalgoorlie, Meekathara and a large number of districts throughout the world. If the thrust of the magma itself were the agent of fracturing, it would be supposed that the magma itself would fill the fractures. That it commonly does so is suggested by the systematized relationships reviewed above.

In certain districts the dikes themselves are fractured and the fractures are filled with ore. Cripple Creek, Colo., and Přibram, Czechoslovakia,

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[31] W. H. Weed: Fort Benton Quadrangle. U. S. Geol. Survey *Folio* 56 (1899).
[32] R. C. Hills: Spanish Peaks Quadrangle. U. S. Geol. Survey *Folio* 71 (1901).

are well-known examples and there are scores of others. At Přibram (Fig. 5) in an area intruded by granitic rocks a system of basic dikes is

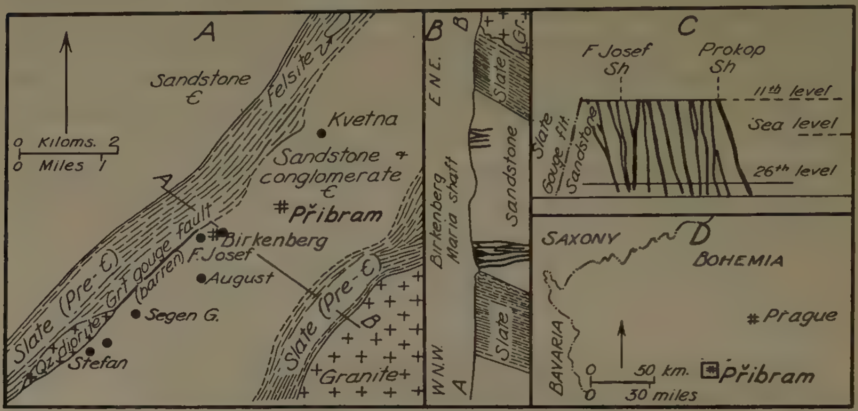

FIG. 5.—MAP AND SECTIONS OF PŘIBRAM DISTRICT, CZECHOSLOVAKIA. (*Data chiefly from J. Schmidt.*)
Line of section *AB* is approximate. In cross-sections most of the veins are narrower than shown. Dark lines in main are basic dikes containing veins.

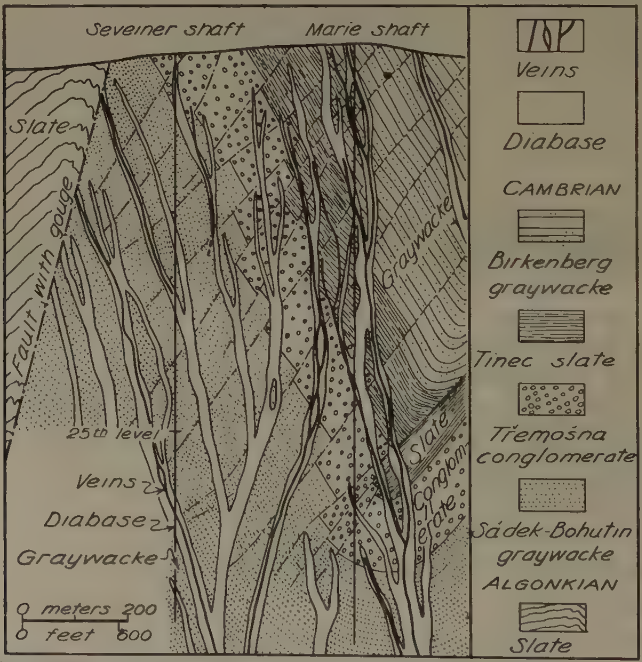

FIG. 6.—VERTICAL SECTION OF PŘIBRAM VEIN SYSTEM, SHOWING VEINS FOLLOWING DIABASE DIKES AND ENDING AT FAULT WITH HEAVY GOUGE. (*After Slavik.*)
Fault is older than veins, since a few veins cut through it.

strongly fractured. Practically all of the veins of the district follow the dikes (Fig. 6). A reasonable explanation for such dike systems

fractured and mineralized at a later episode is that the movements of the main magma fractured the roof of the intrusion, allowing the emplacement of the dikes, and that this was followed by a later fracturing, which had its origin in the vapor pressure built up by the cooling of the batholith.

Elongated Stocks and Lode Systems

Examples of elongated stocks with veins striking approximately parallel to the long axes of stocks include those of Philipsburg, Montana,[33] Grass Valley, California,[34] Bridge River,[35] Rossland, British Columbia,[36] and many others.

The pre-Cambrian shield areas of the earth contain many examples of small elongated cupolas and fingers extending from the batholiths with veins striking nearly parallel to their long axes. That is because erosion has been so deep that parent igneous rocks are generally exposed in the ore-bearing area and patterns may be interpreted more easily. At Porcupine, Ont., the lodes lie at the end of and near the Pearl Lake intrusive,[37] but the age relations of the latter and the lodes are in controversy. Kirkland Lake,[38] Swayze,[39] Moss[40] (Huronian), Sultana,[41] Central Manitoba[42] and many other districts show small stocks with veins approximately parallel to the long axes of the stocks.

The Bourlamaque[43] batholith (Fig. 7) and its satellites in western Quebec, which recently has been mapped by Hawley, show a striking relation between the vein systems and the intrusives. Of eight vein systems developed, seven groups lie nearly parallel to the elongation

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[33] W. H. Emmons and F. C. Calkins: The Geology and Ore Deposits of the Philipsburg Quadrangle, Montana. U. S. Geol. Survey *Prof. Paper* 78 (1913) 1–271.

[34] W. Lindgren: The Gold-quartz Veins of Nevada City and Grass Valley, California. U. S. Geol. Survey, 17th Ann. Rept. (1896) pt. 2, 1–262.

[35] W. G. McCann: Geology and Mineral Deposits of Bridge River Map Area, British Columbia. Can. Geol. Survey *Mem.* 130 (1922) 1–110.

A. M. Bateman: Can. Geol. Survey *Sum. Rept.* for 1912 (1912) 196–198.

[36] C. W. Drysdale: Geology and Ore Deposits of Rossland, British Columbia. Can. Geol. Survey *Mem.* 77 (1912) 1–317.

[37] A. C. Burrows: The Porcupine Gold Area. Ont. Dept. Mines 33d Ann. Rept. (1924) pt. 2, 1–112.

L. C. Graton and H. E. McKinstry: Outstanding Features of Hollinger Geology. Can. Inst. Min. Eng. (1933) 1–20.

[38] E. W. Todd: Kirkland Lake Gold Area. Ont. Dept. Mines 37th Ann. Rept. (1928) pt. 2, 1–175.

[39] N. C. Rickaby: Some Geological Features of the Swayze Gold Area. *Bull.* Can. Inst. Min. and Met. (1933) 204–216.

[40] R. I. Watson: Huronian Gold Mine. Ont. Dept. Mines 37th Ann. Rept. (1928) pt. 4, 109–127.

[41] J. G. Cross: The Sultana Gold Mine. *Can. Min. Jnl.* (1931) 497.

[42] J. F. Wright: Geology and Mineral Deposits of a Part of Southeastern Manitoba. Can. Geol. Survey *Mem.* 169 (1932) 1–150.

[43] J. E. Hawley: Quebec Bur. Mines Ann. Rept. for 1930 (1931) 39–56.

of outlying intrusives or to the elongation of projecting fingers of the central Bourlamaque batholith.

Southern Rhodesia,[44] like Canada, has many deposits that lie in or near small elongated intrusives and strike nearly parallel to the long axes of the intrusives. Examples are Shamva,[45] Sherwood Star,[46] Felixburg,[47] Salisbury Belt,[48] and many others, including probably Rezende. The belt of lodes that are worked in the great Globe, Phoenix and Gaika mines, near the contact of schist and intruding granite, are partly in the granite and partly in invaded schists. Maufe's map shows

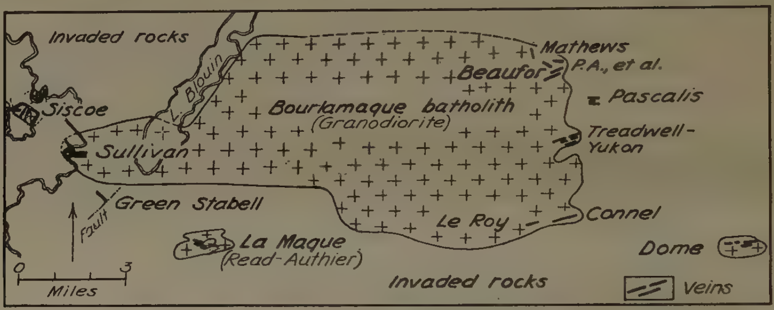

FIG. 7.—MAP OF BOURLAMAQUE, GRANODIORITE BATHOLITH IN WESTERN QUEBEC AND SATELLITIC STOCKS SHOWING GOLD-BEARING VEINS IN FINGERS OF BATHOLITH STRIKING NEARLY PARALLEL TO LONG AXES OF FINGERS, AND IN SATELLITIC STOCKS NEARLY PARALLEL TO LONG AXES OF STOCKS. *(Based chiefly on maps by Hawley.)*

a small marginal roof pendant of schists, and a short distance east of the Gaika mine and a Globe[49] there is a small roof pendant. These and other small bodies of schist in the granite suggest that there was a long body of schist just east of the mines, part of which is eroded. The lodes are evidently of the marginal roof pendant-main contact type (Fig. 2*B*). They recall the relations at Ophir, Calif. In the Battlefields district also several veins have been worked in a narrow granite neck between the main contact to the west and a roof pendant to the east.[50]

In Western Australia the majority of the most valuable lodes lie off the ends of small stocks and of fingers of larger masses. The lodes of

[44] H. P. Maufe: Provisional Geologic Map of Southern Rhodesia. S. R. Geol. Survey (1929).

[45] R. Tyndale-Biscoe: The Geology of the Country around Shamva, Mazal District, Southern Rhodesia. S. R. Geol. Survey *Bull.* 18 (1931).

[46] A. M. MacGregor: The Geology of the Country between Gatooma and Battlefields, Southern Rhodesia. S. R. Geol. Survey *Bull.* 17 (1930) 1–144.

[47] J. C. Ferguson: Mining in the Felixburg District, Southern Rhodesia. S. R. Geol. Survey *Short Rept.* 18 (1931) 1–16.

[48] R. Tyndale-Biscoe: Geology of Part of the Salisbury Gold Belt. S. R. Geol. Survey *Bull.* 19 (1932) 1–35.

[49] S. C. Morgan: Geological Notes on the Gaika Mine, Southern Rhodesia. Guidebook, Excursion C20, 15th Int. Geol. Cong., Pretoria, 1929.

[50] A. M. MacGregor: Reference of footnote 46.

the Golden Mile, Kalgoorlie,[51] of Paddy's Flat, Meekathara,[52] and the Sons of Gwalia[53] lode of Leonora district are similarly situated with respect to small stocks and projecting fingers of larger granitic masses. The deposits of Sir Samuel,[54] Golden Ridge,[55] and of other small mining

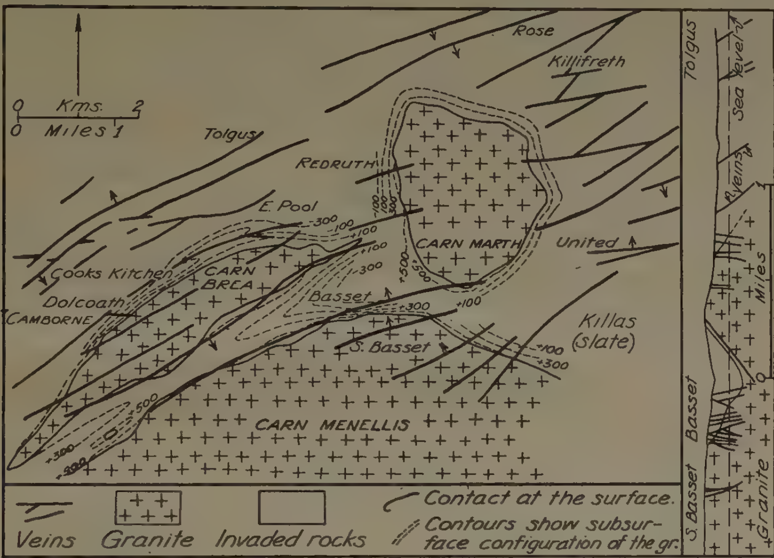

FIG. 8.—MAP SHOWING CARN BREA AND CARN MARTH CUPOLAS AND TIN AND COPPER VEIN SYSTEMS NEAR CAMBORNE, CORNWALL, ENGLAND. (*Data from various maps by McAlister, Hill and Flett.*)

Contours show contact of granite and invaded rocks at elevations shown above and below sea level.

districts are also located on or near the long axes of small intrusives. So are the great copper-gold lodes of Moonta in South Australia. The deposits of Wallaroo near by lie close to the end of the Moonta stock but strike across its axis.

In the Pilbara[56] district in the northwestern part of Western Australia there is a striking relation of the mining districts to cupolas and fingers

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[51] F. L. Stillwell: Geology and Ore Deposits of the Great Boulder, Kalgoorlie. West. Aust. Geol. Survey *Bull.* 94 (1929) 1–110, with atlas.

C. O. G. Larcombe: The Geology of Kalgoorlie. *Trans.* Aust. Inst. Min. Engrs. (1912) **14,** 1–327; *idem* (1927) **67,** 248–268.

[52] The Geology and Ore Deposits of the Meekathara Murchison Gold Field. West. Aust. Geol. Survey *Bull.* 68 (1916) 1–342.

[53] C. F. V. Jackson: Geology and Auriferous Deposits of Leonora, Western Australia. W. Aust. Geol. Survey *Bull.* 13 (1904) 1–47.

[54] C. G. Gibson: The Geology and Mineral Deposits of Lawlers, Sir Samuel and Dorlat. West. Aust. Geol. Survey (1907) 1–73.

[55] C. S. Honman: The Geology of the Country South of Kalgoorlie. West. Aust. Geol. Survey *Bull.* 66 (1916) 1–75.

[56] A. G. Maitland: Geological Features and Mineral Resources of the Pilbara Goldfield. West Australia Geol. Survey *Bull.* 20 (1894) 1–51; also *Bulls.* 15, 23, 40.

of the batholith, the deposits lying at the ends of the intrusions, as is shown at Marble Bar, Bamboo, Yandicoogina, Western Shaw, etc.

Lodes parallel to the long axes of associated cupolas are found in most of the great tin-bearing regions of the world and in many of the minor ones. Near Camborne in Cornwall the great Dolcoath and associated lodes, which together form one of the greatest systems of tin deposits that have been worked, lie nearly parallel to the axis of the Carn Brea and Carn Marth cupolas. The upper contact of these cupolas has been contoured by McAlister, Hill and Flett.[57] The vein system is

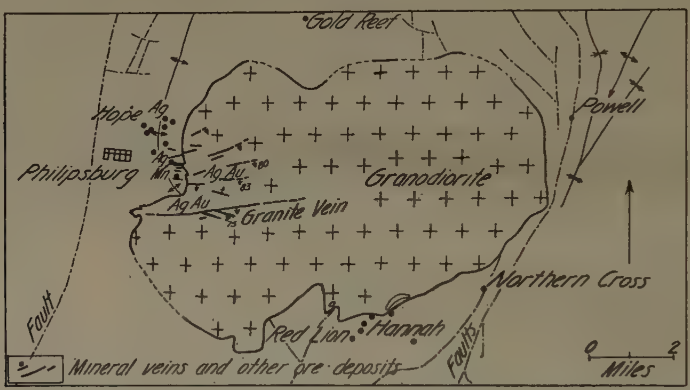

FIG. 9.—PLAN OF GRANODIORITE MASS OF PHILIPSBURG BATHOLITH, PHILIPSBURG, MONTANA. (*After W. H. Emmons and F. C. Calkins.*)
Long axis of batholith cuts across major faults and folds of region almost at right angles, and mineral veins strike approximately with long axis of intrusive.

superimposed on the contour map (Fig. 8.) The great Kit Hill-Gunnislake vein system near Tavistock shows similar relations and the lodes at the southeast contact of the Bodminmoor massive lie parallel to the axes of an outward projecting finger of the granite mass.

The disseminated copper ores in porphyry and in other acidic rocks have been treated as a group in another paper,[58] where it is shown that many of the productive areas of copper ore lie in belts or zones along the upward swells of the intrusives. This is well shown at Cananea, Sonora. It is not claimed that the individual fractures of these mineralized areas tend to lie parallel to the elongation of the porphyry intrusions, but that the long axes of the zones of shattering in which the primary deposition was concentrated were controlled by the shapes of the contacts of the intrusive and its roof.

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[57] D. A. McAlister, J. B. Hill and J. S. Flett: Geology of Falmouth and Truro and of the Mining District of Camborne and Redruth. *Mem.* Geol. Survey of Great Britain (1906) 1–334.

[58] W. H. Emmons: Relations of the Disseminated Copper Ores to Igneous Intrusions. *Trans.* A. I. M. E. (1927) **75**, 797–815.

Lodes Crossing Strike of Major Structural Features

It may be urged that the long axes of stocks and the major mineralized fractures lie parallel because both follow lines that are loci of weakness. That may be true of some districts, but it is not universally true, for at places both the long axes of the intrusive stocks and the veins strike across the lines of tectonic deformation. At Philipsburg, Mont., for example, the major faults and the axes of folds strike nearly north, whereas the long axis of the Philipsburg batholith, as shown by Calkins,[59] strikes east nearly at right angles to the lines of major deformation of the area. In this district the major veins strike approximately parallel to the long axis of the Philipsburg batholith and nearly at right angles to the lines of major deformation as represented by axes of folds and of major faults (Fig. 9).

Mineralization of Major Fractures

It is well known that few faults of great throw are mineralized, even in areas of strong mineralization. That may be due to impermeable gouge developed in them by movements, as was pointed out by Ransome,[60] or it may be that they do not extend to the sources of mineral-bearing solutions.

There are, however, a considerable number of faults with moderate throw that are mineralized and some of these carry gouge, as do the veins of the Blue vein system of Butte, Mont. Certain vein systems that have no obvious relation to the axes of cupolas or to fingers of stocks near by may nevertheless lie in fractures that have been reopened by pressure of the vapor released by cooling magmas. If strong fissures suitably located were available, these, regardless of their orientation, might be reopened with less pressure than would be required to form new ones, and they would be utilized as channels for escaping aqueous fluids that deposit lode ores.

One of the regions, where no clear-cut relation between the lodes and the shapes of batholiths exists, is in central Germany, particularly near the Harz Mountains and in the Saxon Erzgebirge. In this region the lodes generally strike northwest parallel to the direction of the Hercynian fracturing, or northeast parallel to the direction of Variscian folding. Apparently earlier lines of weakness determined the direction of the ore-bearing fractures.

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[59] W. H. Emmons and F. C. Calkins: Geology and Ore Deposits of the Philipsburg Quadrangle. U. S. Geol. Survey *Prof. Paper* 78 (1913) 1–2.

[60] F. L. Ransome: The Relations of Certain Ore-bearing Veins and Gouge-filled Fissures. *Econ. Geol.* (1909) **3**, 331–337.

Stocks Contracting Downward

There are certain stocks that become narrower in depth. These may broaden into typical cupolas at greater depth, but that is not proved. Stocks intruded near the surface are likely to flare out into funnel-shaped bodies because with pressure decreasing near the surface there is less resistance to lateral expansion. The intrusive stock of Nagyag, in the Transylvanian Erzgebirge,[61] and the Potosí stock of Bolivia[62] are well known examples of stocks that narrow downward like inverted cones. These intrusives are of very late age and were formed near the surface. That is true also of Ely, Nev., where deep exploration has shown that the stocks contract with depth, and where, according to Locke,[63] only a few hundred feet have been eroded since the deposition of the ore. The Fierro-Hanover intrusive in New Mexico, as shown by Schmitt,[64] narrows with depth.

In the few examples of metallized upward flaring stocks, the veins or mineralized zones generally lie rudely parallel to long axes of the intrusives. That is true in the Transylvanian Erzgebirge, at Ely, and probably some of the stocks in Bolivia, although maps of only a few of the vein systems in Bolivia are available. In general the parallel alignment of veins and of the long axes of cupolas is more marked in and around deep-seated cupolas than in stocks formed near the surface.

Small Subsidence Areas

In certain regions of strong mineralization there are small areas of subsidence where rocks are broken and at places faulted downward. Locke[65] has explained such areas by "mineralization stoping." He believes that the solutions first entering ore channels were strongly dissolving solutions and that the ore-depositing and rock-cementing solutions came later. That explanation may be a true one for certain deposits, but if gas cones form at pinnacles of the cores that lie below cupolas it is possible that small areas of subsidence may form by overlying material slumping downward to fill space formerly occupied by gas.

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[61] M. von Palfy: Reference of footnote 28.

[62] F. Ahlfeld: Die Erzlagerstätten der Tertiären Magma-Provinz der Bolivianischen Zentralanden. *N. Jahrb. Min.* (1932) **65B**, 286–446.

[63] A. Locke: Ore Deposits of the Western States (Lindgren Volume), 621. New York, 1933. A.I.M.E.

[64] H. A. Schmitt: The Central Mining District, New Mexico. Page 187, this volume.

[65] A. Locke: The Formation of Certain Orebodies by Mineralization Stoping. *Econ. Geol.* (1926) **21**, 431–453.

Examples of subsidence of small areas that are marked by strong mineralization are found at Tintic Standard[66] mine (Fig. 10) where beds of limestone replaced by ore are faulted down to form a graben about 1600 ft. across. At Ophir, Utah (Fig. 11), a system of mineralized faults makes a graben about 1.5 miles wide. These faults are closely spaced and the graben occupies the crest of a greater anticline. At the Waihi mine, New Zealand (Fig. 12) the Martha and Royal lodes outline a graben about 1600 ft. across and a small graben is developed in the Cusi-Mexicana mine at Cusihuariachic, Chihuahua, Mexico (Fig. 13).

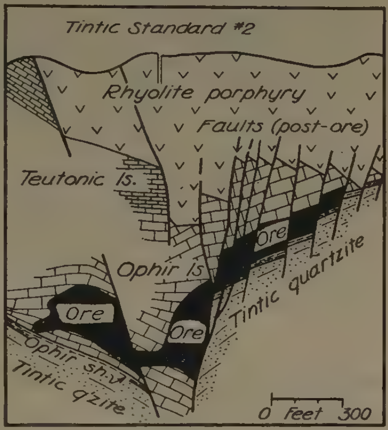

Fig. 10.—Cross-section of Tintic Standard mine, East Tintic, Utah. (*After G. W. Crane.*)
Orebodies form V-shaped series of fault blocks or a graben.

At Los Pilares mine, Nacozari, Mexico, where most of the ore forms the walls of an upright, nearly cylindrical body, the plan of the body is elliptical and about 2000 ft. long and 1000 ft. wide. The country rock is latite, which rests on andesite, and the contact has sagged downward in the pipe some 200 ft. and in the center of the pipe more than that.[67]

The Colorado pipe, Cananea, Sonora, Mexico, is one of the greatest high-grade copper deposits developed in recent years and is said to contain a billion pounds of copper. A section of this deposit by Billingsley is presented by Locke:[68] (1) Flat-bedded tuffs are intruded by (2) a quartz-porphyry plug about 800 ft. in diameter. Within this pipe are nested inverted hollow cones of (3) quartz-orthoclase rock which replaces the quartz-porphyry plug, and within the quartz-orthoclase cone is (4) one of massive ore with chalcopyrite and bornite. Inside the latter is (5) a cone of brecciated ore. Within that is (6) a cone of breccia with pyritized sericitized rock below commercial grade.

The nearly circular area of disseminated copper ore at Santa Rita, N. M., which is 4000 ft. in diameter, is considered by Locke to represent a subsidence circle and also the deposit at Ajo, Ariz., which has an area 4000 by 2000 feet.

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[66] G. W. Crane: Notes on the Geology of East Tintic. *Trans.* A.I.M.E. (1926) **74,** 147–162.

P. Billingsley: The Utilization of Geology in Tintic, Utah. Ore Deposits of the Western States (Lindgren Volume), 716–722.

P. G. Morgan: Geology and Mines of the Waihi District, Hauriki Goldfield, New Zealand. N. Z. Geol. Survey *Bull.* 26 (1924) 1–218.

[67] A. Locke: Reference of footnote 65, 432.

[68] A. Locke: Reference of footnote 63, 616.

Two additional metallized areas should be mentioned here. They are not marked by subsidence but in their rudely cylindrical outlines

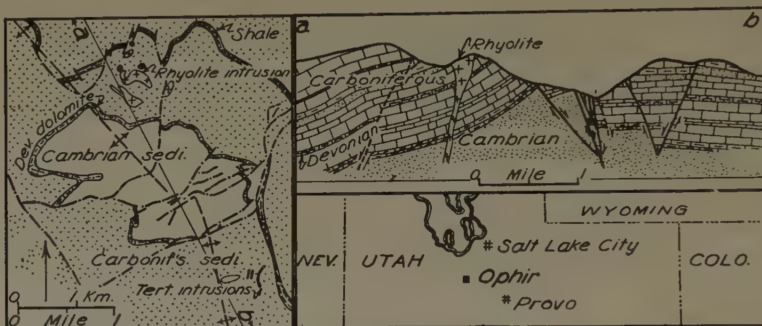

FIG. 11.—MAP AND SECTION OF OPHIR DISTRICT, UTAH. (*After James Gilluly.*) Silver-lead deposits occur in the fault fissures and replace limestone beds in faulted area.

and fracturing they resemble Nacozari. One of these, the Patch, a mine southwest of Central City, Colo., is an elliptical area 750 ft. long and

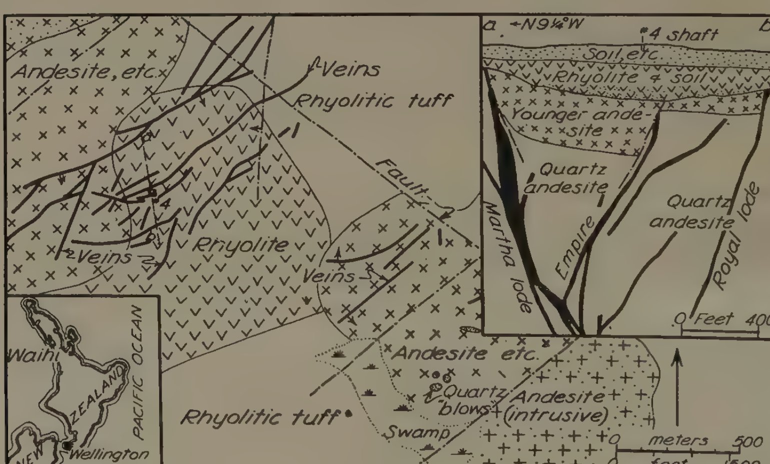

FIG. 12.—MAP AND CROSS-SECTION ON LINE *ab* OF PART OF WAIHI GOLD-MINING DISTRICT, NEW ZEALAND. (*Data from Morgan.*)
Lodes in andesite crop out as shown, but are covered over by rhyolite where positions near base of rhyolite are shown on map. Cross-section shows graben or down-faulted block about 1500 ft. across.

400 ft. wide that dips steeply to a depth of at least 1600 ft. At places the fracturing is so intense that a friction breccia is developed.[69]

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[69] E. S. Bastin and J. M. Hill: Economic Geology of Gilpin County, and Adjacent Parts of Clear Creek and Box Elder Counties, Colorado. U. S. Geol. Survey *Prof. Paper* 94 (1917) 235–237.

The Jessie[70] mine, 2½ miles northeast of Breckenridge, Colo., is in an elliptical area 900 ft. long and 600 ft. wide in quartz monzonite. Within the area the rock is broken by irregular fractures and is mineralized with lean gold-silver ore.

When one considers the great number of mining districts where no such subsidence areas have been observed, the examples cited above do

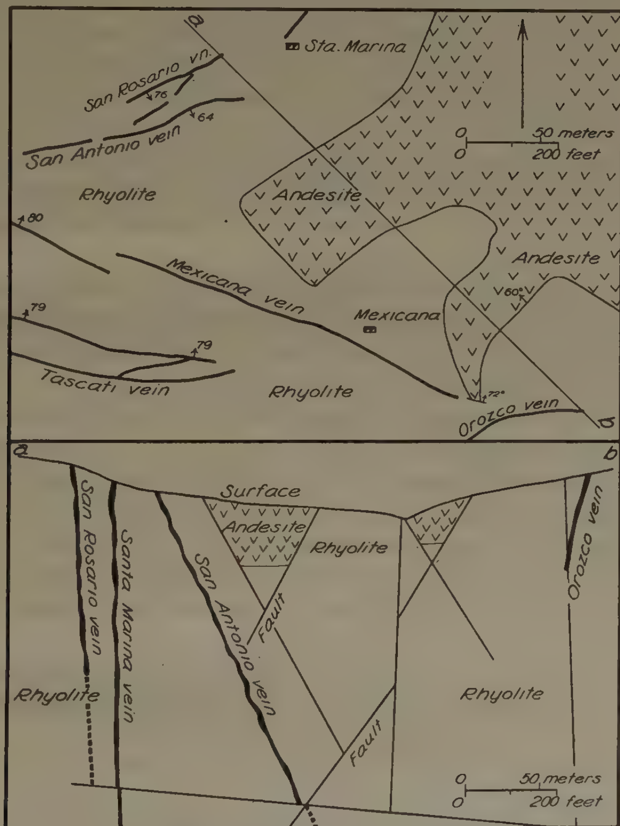

FIG. 13.—MAP AND SECTION OF PART OF CUSIHUIRACHIC DISTRICT, CHIHUAHUA MEXICO. (*After Hugh Roberts.*)

not seem to be numerically impressive. It is possible that these areas are more numerous than is generally supposed. In areas of uniform rock formations, small graben, even if present, would be difficult to discover.

SUMMARY

A cooling granitic magma containing considerable water when crystallizing to form anhydrous minerals will expel water and other

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[70] F. L. Ransome: Geology and Ore Deposits of the Breckenridge District, Colorado. U. S. Geol. Survey *Prof. Paper* 75 (1911) 144–147.

volatile constituents, and these at the solidification point of granite, which is about 600°C., will exert a high vapor pressure. Considering the results of Morey's experiments, it is reasonable to suppose that this pressure is great enough to lift two or three miles of granite. Thus it appears probable that cooling granitic batholiths, which supply the solutions that deposit the majority of the lode ores of the earth, also on cooling form many of the fractures that become the ore channels.

The theory that magmas supply fluids under pressure is a very old one and has been expressed in several of the earlier papers on petrology and economic geology. Graton[71] considered certain gold-bearing fractures of the Appalachian region to have opened by pressure from below, and according to Spurr[72] the deposits of Silver Peak, Nev., fill openings formed by intrusions. In a recent paper, Wandke[73] considers the vapor pressure of cooling magmas to have opened certain fissures in Guanajuato, Mexico.

For several years the writer has been engaged in the studies of batholiths of the earth[74] and the relations of associated mineral veins to them, and has found sufficient data to compile maps of nearly all of the more important mineral-bearing areas of the earth producing ore from lodes. These maps show the vein patterns of the districts and their relations to intrusive stocks where these are exposed. A great many of the small stocks are nearly elliptical in outcrop, and one axis being much longer than the other; very few are rudely circular. Broad projecting fingers extend outward from many small stocks and from larger batholiths. The majority of the veins situated in and near the small stocks and projecting fingers lie parallel to their long axes. The normal small stock or cupola broadens downward and so its top has about the shape of the top of a hay rick. After the shell of the top of the stock solidified the solid part would rest on a pinnacle of the core of the batholith—a partly

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[71] L. C. Graton: Gold and Tin Deposits of the Southern Appalachians. U. S. Geol. Survey *Bull.* 293 (1906) 59.

[72] J. E. Spurr: Ore Deposits of Silver Peak, Nevada. U. S. Geol. Survey *Prof. Paper* 55 (1906) 11; The Ore Magmas (1923) 100.

[73] A. Wandke: Ore Deposition in Open Fissures Formed by Solution Pressure. *Trans.* A. I. M. E. (1931) **96,** 291–304.

[74] W. H. Emmons: Primary Downward Changes in Ore Deposits. *Trans.* A. I. M. E. (1924) **70,** 964–994.

Relations of Metalliferous Systems to Igneous Intrusions. *Trans.* A. I. M. E. (1926) **74,** 29–70.

Reference of footnote 58.

The Origin of the Deposits of Sulphide Ores in the Mississippi Valley. *Econ. Geol.* (1929) **24,** 221–271.

Prospecting for Gold in the Shield Areas of Canada, Siberia, Southern Rhodesia and Western Australia. *Trans.* A. I. M. E. (1932) **102,** 175.

Reference of footnote 8.

Reference of footnote 1.

liquid body which also would have the shape of a hay rick. If pressure were exerted equally from the partly liquid underlying body on the shell, the mechanics of the situation require that cracks and shear zones form parallel to the axis of the elongated cupola and extend upward from the cupola. Comparison of nearly all of the chief metallized cupolas of the earth shows that these relations are very common, and thus they support the theory that the vapor pressure generated from the cooling magma has opened the fractures in the overlying rocks.

It does not follow that all lodes occupy fractures that were formed by thrust of vapor that was generated by a cooling magma. It is well known that only a few of the faults of great throw are mineralized. They are generally barren even in areas of strong mineralization. Certain fractures that are faults of moderate throw are mineralized, however, and many of these are not parallel to the long axes of stocks. These may be ancient fractures formed during the episode of deformation that commonly precedes the rise of batholithic masses. Where suitably spaced as to the source of pressure, they may have been reopened through the pressure generated by the crystallizing magma of the batholith.

Briefly, some of the major events that are believed to attend the rise and cooling of a batholith may be stated in supposed chronological order as follows:

1. Rise of batholith by thrusting, fluxing and stoping its way up.

2. Release of fluids and some contact metamorphism around certain supersaturated magmas (but probably few magmas are supersaturated at this stage).

3. Solidification of border phase of batholith which is formed before much differentiation of magma has taken place and which therefore is generally more basic than the main batholith.

4. Rise of light salic crystals, fall of heavy femic crystals, differentiation to form masses of granitic magma which contains a concentration of the chief volatile constituents of magma.

5. Solidification of the hood around the top of the still partly liquid core of batholith and further crystallization of the core.

6. Rise of pegmatites into hood and roof of batholith.

7. Rise of steam bubbles and metalliferous volatile materials from liquid core to form cones of gas or of gas-charged magma at pinnacles or high parts of core.

8. Failure of hood and roof which form the container for the gas-charged magma and fracturing of cupolas of batholith, so that fractures generally are systematically disposed in and about cupolas and projecting fingers of the hood of the batholith.

9. Continued cooling and crystallization of core of batholith with volatiles boiling out of the main mass to liquefy in fracture channels where they deposit ore in fissures and replace wall rocks along them.

10. Collapse at places of small areas above pinnacle cones of gas or of gas-charged magmas and subsidence due to shrinkage resulting from cooling and from expulsion of gases from pinnacles.

11. Cementation by ore of collapsed areas and of later fractures that form where the hood has become tight, so that high vapor pressure again may be built up.

12. Solidification of the base of batholith cutting off any additions of metalliferous fluids from a deep source.

13. Progressive downward solidification of the barren core.

14. Fracturing of barren core.

15. Deposition of pegmatites without metals, of barren quartz veins and of practically barren quartz pyrite veins in the core of the batholith. Volatiles still escape from the core but do not carry appreciable metals.

16. Solidification of the core is completed.

Acknowledgments

The work on which this paper is based has geen generously supported by the committee of the Graduate School of the University of Minnesota, which is gratefully acknowledged by the author. Most of the funds have been used for the preparation of maps and for the translation of foreign literature. The writer wishes particularly to acknowledge the assistance of Dr. M. H. Frohberg and Mr. W. I. Gardner, his associates in the research, for their skilful services and for their sympathetic understanding of the problems presented. He wishes to thank also his colleague, Dr. F. F. Grout, who many times has placed at his disposal an almost encyclopedic knowledge of intrusive rocks.

DISCUSSION

(*W. E. Wrather presiding*)

A. C. Lane,* Tufts College, Mass. (written discussion).—Is it not likely that in many cases the granite magma was cooled below the melting point of the constituents, and by the principle of eutectics are not the abundance of atoms and the solubility of crystals in the magma quite as important as the melting point? In the famous Pigeon Point Cove of Cape Ann, and in other places, not infrequently we find large phenocrysts of feldspar in what may be a basic facies of the granite.

Also, if bubbles are the vehicles by which metals are carried up, will there be a downward limit to ore deposits at the time of formation? The source batholith, it would seem, could not be too deep. Otherwise bubbles could not form at a depth above the critical pressure of the water and other mineralizers. Would Dr. Emmons in this way explain the absence of ores around many granites—that their injection was too deep to allow bubbles to segregate the ores?

W. H. Emmons (written discussion).—I agree with Professor Lane that granites usually solidify at temperatures below the melting points of their minerals. The

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* Professor of Geology and Mineralogy, Barnum Museum, Tufts College.

recent work of Goranson[75] shows pretty definitely, I think, that granites solidify at a little above 600° C., whereas the chief constituents of granites solidify at considerably higher temperatures. The eutectic principle as suggested by Professor Lane offers a probable explanation of this phenomenon.

As to whether metals start from the magma as gases or not, I think they do perhaps in bubbles of steam into which the metallic gases are distilled. In this I follow Fenner.[76]

C. H. Behre, Jr.,* Evanston, Ill.—In this paper, stimulating and enlightening as it is, there are nevertheless certain fundamental and significant errors. In the first place, I believe that the author has either misstated his statistical observations or has given them the wrong interpretation. Fractures produced by the doming up of the roof of a cupola are tensional; theoretically they should radiate outward from the point of greatest lifting—the crest of the cupola. If the cupola is elliptical *more* fractures should be at right angles (or nearly so) to the long axis of the cupola than parallel to that axis—just the contrary of Dr. Emmons' assertion. On the other hand, the *stronger* fractures (i.e., those that would tend to gape most widely because developed on arcs having the smaller radius of curvature) should be parallel to the long axis. I suspect it is these alone, being naturally most mineralized, that were found by the author, and he was therefore misled into believing that they were dominant in *number*.

It is also debatable whether he is correct in concluding that the prominent elongated fractures of mineralized areas above cupolas are chiefly the result of the upthrust of the magma. On the contrary, it is certain that many plugs are elongated parallel to major thrusts because, rising along the thrusts, they spread out more readily in that direction. Thus plugs and fractures are elongated by preexisting tectonic conditions, instead of being themselves the *cause* of the elongation of the fractures.

W. H. Emmons (written discussion).—Professor Behre believes that fractures produced by doming the roof of a cupola should radiate outward. There is not one example known of a set of ore-bearing fractures radiating from a distinctly elongated cupola. The Lands End massive in Cornwall and the north end of the Arbus mass, Sardinia, have mineralized fractures rudely radial with respect to the intrusives, but the Lands End mass and the north end of the Arbus mass are nearly circular in outline and the radial pattern should be expected, as is pointed out in my paper (page 17).

Dr. Behre says that the strongest fractures and those that are most commonly mineralized should be parallel to the axis of elongation of the cupola, but that I was misled into believing that they are dominant in number. The title of the paper he discusses shows that it is the ore-bearing fractures that are treated and not the joints and unmineralized fractures.

In regions of strong mineralized fractures geologists rarely map the joints and feebly mineralized fractures. There are a few exceptions to this practice but I do not know of an elongated cupola with strong mineralized fractures parallel to its elongation and with more numerous cross fractures. In my experience the strong sheeting in a cupola tends more often than otherwise to lie parallel to the stronger fractures.

Dr. Behre says also that plugs (stocks) are elongated because of pre-existing tectonic conditions. That is true. There are many ore-bearing fractures that have no apparent relation to any cupolas of intrusives. These are treated on page 23.

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[75] R. W. Goranson: Some Notes on the Melting of Granite. *Amer. Jnl. Sci.* (1932) [5] **23,** 226–236.

[76] C. N. Fenner: Second reference of footnote 9, 71.

* Associate Professor of Geology, Northwestern University.

L. V. Bell,* Quebec, Canada (written discussion).—Dr. Emmons advances the theory that ore-bearing fractures in and closely related to granitic intrusive bodies throughout the world are caused by the cooling and solidification of those bodies in the course of which gas pressures are built up and become the principal agency effective in the development of such fractures. The fracturing, in other words, is held to be dependent upon internal forces generated by the intrusives themselves as distinct from external or regional deforming stresses acting upon those bodies. Among many others, the vein fractures of the Bourlamaque batholith and its satellites in the Abitibi district of Quebec are cited in support of the theory as outlined above.

Study of the mineral deposits connected with the Bourlamaque and the near-by Pascalis-Tiblemont batholiths, and with associated smaller intrusives, has led A. M. Bell and the writer to entertain a very different view concerning the structural history of the deposits[77]. That paper need not, therefore, be reviewed here other than to point out some of the principal factors leading to conclusions opposed to those of Emmons concerning the origin of identical fractures.

In the first place, the writer recognizes a close genetic affinity between the deposits and the intrusives with which they occur, and to this extent is in accord with Emmons. The fracturing, however, is held to have originated from *external* dynamic forces of regional character as distinct from *internal* stresses peculiar to the intrusives themselves. The following is cited in support of this contention.

The fracture pattern of the intrusives is related to the regional structure in such a manner as to imply its derivation from similar forces. Speaking broadly, the structures in each case indicate shortening or compression in a north-south direction. The regularity of the fracture system throughout both the intruded and intrusive rocks favors the view that it has developed under uniform conditions acting more or less as a unit. The prevailing strike of the fractures, particularly in the softer and more foliated, invaded rocks is east-west, corresponding to the regional cleavage or schistosity. Emmons' remark that "systems of rudely parallel veins are more common than all others combined" comes to mind here, and although the present discussion is confined to one district, it seems probable that similar reasoning might apply elsewhere, parallelism of fractures to be accounted for by the direction of shearing or regional cleavage. In addition to their prevailing east-west strike, fractures in one of the major intrusive masses in particular assume a north, northeast and a northwest direction. The fractures, therefore, are those that might be expected to develop theoretically through deformation as illustrated by the strain ellipsoid. Variations in strike from those given above do occur, however, but are due essentially to changes in the physical character of the rock through the presence of small inclusions of softer rocks within the harder and more competent ones. This factor, indeed, has proved an important one in the localization of some of the gold-bearing veins.

Emmons has stated that gold-bearing fractures in the Bourlamaque batholith strike parallel to the elongation of its projecting fingers. The writer mapped the eastern border along which over half the vein systems connected with the batholith occur, but failed to find any projections to which the term "fingers" might properly be applied although presumably it is at least in part from these maps that Emmons has taken his data. It might be said more accurately that the strike of the vein fractures is nearly at right angles to the eastern granodiorite contact, but parallel to the elongation of the body as a whole. Emmons' further observation that other fractures lie parallel to smaller "outlying" intrusives is quite true, but this is equally true of the larger, batholithic masses. The elongation of the intrusives themselves

* Geologist, Bureau of Mines, Province of Quebec.

[77] A. M. Bell and L. V. Bell: Structural Features of Certain Gold Deposits in Western Quebec. *Econ. Geol.* (1935) **30**, 347.

is another factor that is controlled by regional structure and is in this way related to the strike of the vein fractures. Thus the regional structures, principally folding and shearing in the older rocks of the Abitibi belt, is east-west corresponding to the elongation of the bodies intrusive into them.

Speaking more generally, does Emmons' observation that there is a definite controlling relationship between the shapes of the intrusive bodies as now exposed and the direction of associated, ore-bearing fractures, support his theory of their derivation from gaseous pressures? Without in any way questioning the possibility of the existence of such pressures, or the assumption that they might under certain circumstances be effective in fracturing the rock, it would seem that resultant fracturing would, on the contrary, be highly irregular, and concentrated only in certain spots in the vicinity of the vents through which the gases might be assumed to have escaped. It seems difficult to reconcile the existence of a broad fracture pattern bearing a definite relationship to the shape of the intrusive body as a whole with the assumption that it was derived from gaseous pressures, presumably of explosive nature.

Relative displacements along gold-bearing fractures are other criteria indicative of the nature of the stresses involved. Although in most cases studied they are probably small, displacements along certain of the fractures connected with the Pascalis-Tiblemont intrusives show a fairly strong, horizontal component, which would suggest the action of external forces and not those of purely internal character as required by Emmons.

Several of the gold-bearing fractures, particularly some of those along the eastern border of the Bourlamaque batholith, are definitely related to a uniform and rather extensive foliation of the rock. Elsewhere some of the deposits are subsidiary to highly sheared zones. These are structures that the writer believes would normally result through deformation caused by external stresses and, indeed, could not well develop in any other manner. On the whole it appears to the writer that the evidence provided by the vein structures of the Bourlamaque and related intrusives does not support the theory set forth by Emmons.

W. H. Emmons (written discussion).—The map showing the outline of the Bourlamaque batholith and its satellites and associated veins (Fig. 7) seems to me to show definite relations between the orientations of veins and elongations of satellites and fingers of the batholith. I have visited only the mines of the west half of the Bourlamaque mass, and I have used data presented by Hawley for the map[78]. His mapping where I have followed it is very accurate and I assumed that his mapping of the east margin also was accurate. In a country where so much of the contact is covered with drift, however, there may be more than one interpretation of the data.

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[78] J. E. Hawley: Reference of footnote 43.

Structural Associations of Certain Metalliferous Deposits in Southwestern United States and Northern Mexico

By Harrison Schmitt,* Member A.I.M.E.

(New York Meeting, February, 1933)

During the past decade the writer has studied and mapped certain ore deposits and their structural associations in the states of Chihuahua, Durango, New Mexico and Arizona, and he believes that these deposits, with the exception of the manto-chimney, are representative of the principal types in the area of the states named. In this paper the deposits are described; then generalizations are drawn so far as seems appropriate.

Hanover, New Mexico

The Hanover, New Mexico, zinc deposits were briefly described by Lindgren and others,[1] Paige[2] and recently in more detail by Schmitt.[3] These, the kind ordinarily called contact metamorphic, border the southern end of an oval area of granodiorite intrusive ¾ mile wide and 2½ miles long (Fig. 1). The granodiorite has intruded, folded, and metamorphosed sedimentary and igneous rocks, which range in age from pre-Cambrian to Upper Cretaceous. About 90 per cent of the ore has replaced coarse, recrystallized, pure, fossiliferous, lower Mississippian, nonmagnesian limestone (Hanover limestone) 110 ft. thick;[4] about 75 per cent of it occurs in the upper 50 ft. of this horizon just below an 18-ft. lower Pennsylvanian shale bed, which lies on a locally inconspicuous unconformity representing upper Mississippian time.

The orebodies show five shapes or attitudes, each dependent on a special structural situation:

1. Most of the ore occurs as podlike, thick lenslike or other "three-dimensional" shoots extending from top to bottom of the Hanover limestone and lying adjacent to the outer contact of a silicate zone largely of andradite, which follows the intrusive contact (Figs. 1 and 2).

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* Consulting Mining Geologist, El Paso, Texas.

[1] W. Lindgren, L. C. Graton and C. H. Gordon: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68 (1910) 305–317.

[2] S. Paige: The Silver City Folio No. 199, U. S. Geol. Survey (1916).

[3] H. Schmitt: The Central Mining District, New Mexico. Page 187, this volume.

[4] This is the average thickness in undisturbed areas. Near the contact metamorphic zone deformation has thickened and thinned the ore-bearing limestone (Reference of footnote 3).

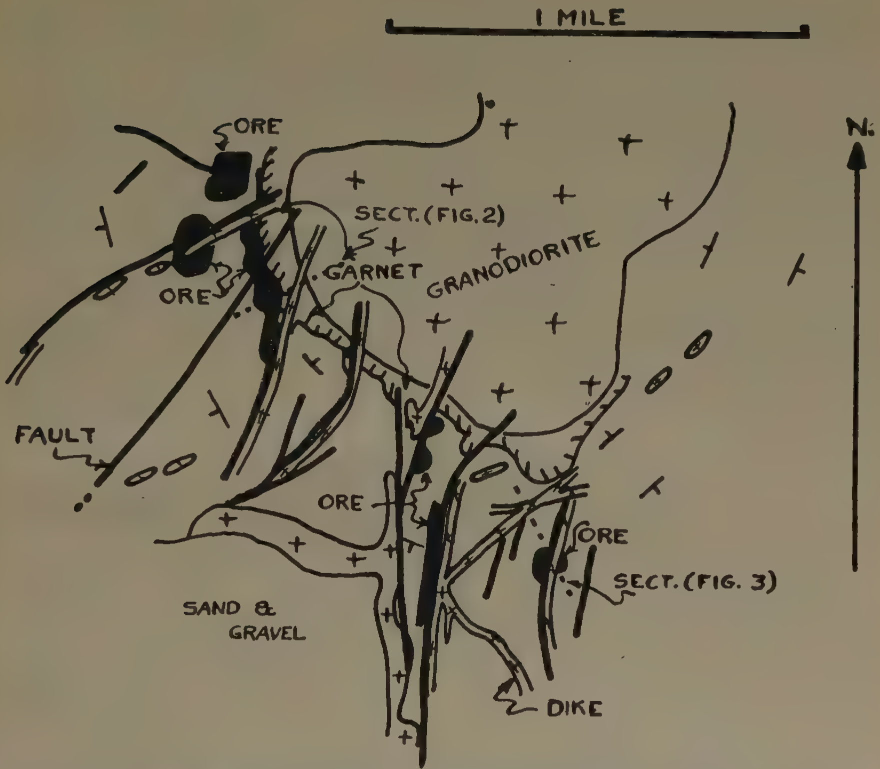

FIG. 1.—SURFACE GEOLOGIC PLAN OF HANOVER, NEW MEXICO, ZINC DISTRICT.
Greatly simplified reproduction of a large-scale map by H. Schmitt. Drawn to scale.

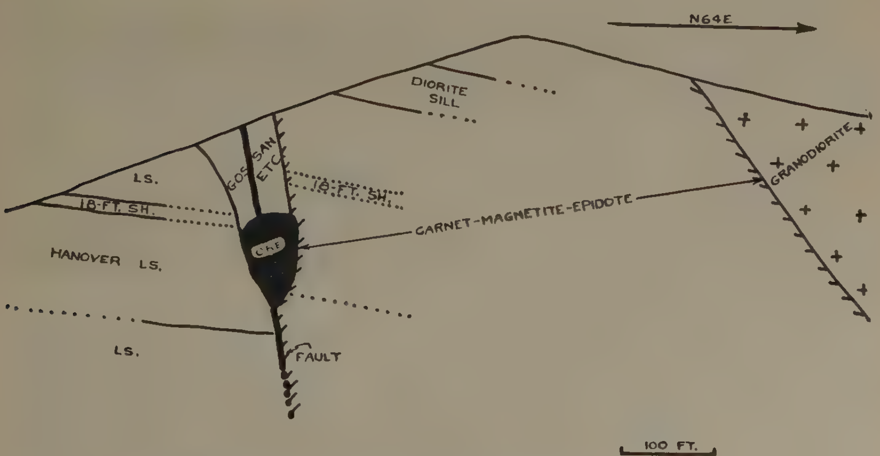

FIG. 2.—GEOLOGIC SECTION SHOWING CROSS-SECTION OF PODLIKE OREBODY AT HANOVER, NEW MEXICO.
Exact reproduction of the original section by H. Schmitt, which was based on large-scale mapping, diamond-drilling and the shape of the worked-out stopes.

In further detail these orebodies were localized by high-angle faults which either coincide with the garnet-limestone contact or cut it at a large angle.

2. Next in importance are vertical "two-dimensional" or tabular orebodies, virtually veins, which follow the contacts of high-angle dike-faults that radiate from the main intrusive contact (Fig. 1). The ore extends from top to bottom of the Hanover limestone with little change in width, except in places an increase just under the Pennsylvanian shale bed, and shows a tendency to weaken or disappear near the bottom of the favorable horizon. One of these "veins" has a strike extension of more than 1000 ft. and in this case the ore, although connected, can be further subdivided into shoots for which the detailed localizing factors are not obvious.

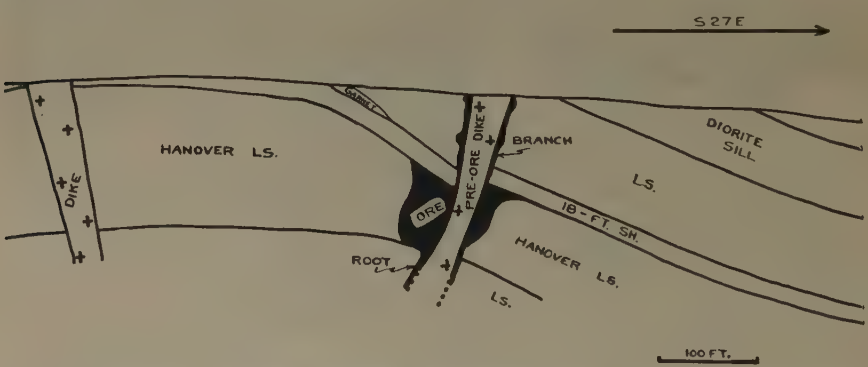

FIG. 3.—GEOLOGIC SECTION SHOWING CROSS-SECTION OF CONELIKE OREBODY AT HANOVER, NEW MEXICO.

Exact reproduction of the original section by H. Schmitt, which was based on large-scale mapping and exhaustive diamond-drilling.

A feature of this fissure or vein ore is that the greater part lies on the west contacts of the associated dikes. In only two of the six occurrences was there additional minor ore on the east contact. This preference is the more curious because the west side of a given fault-dike may be either the hanging or foot, or up or down wall.

3. Third in importance are horizontal or gently dipping (0° to 10°) "two-dimensional" or blanket orebodies, which follow the contact of the Hanover limestone with the overlying shale and are associated with gently flexed anticlines or synclines.

4. One 3500-cu. ft. orebody has the shape of an inverted cone, the base of which abuts the bottom of the 18-ft. Pennsylvania shale bed (Fig. 3). It is associated with the intersection of a fault dike and a sharp change in the dip of the sedimentary wall rock.

5. Another orebody about 350 ft. long and 30 ft. in diameter is "one-dimensional" or chimneylike, is enclosed by the Hanover limestone, and dips 30° toward the main intrusive. The causes for this form and localization are not apparent, but there is reason to believe that the

chief factor was the intersection of a flat thrust, which dips toward the intrusive, with a high-angle normal fault.

These five types of ore occurrence account for all the known ore. That is, every known orebody has a distinctive structural association and apparently a structural reason for being. The 18-ft. shale bed seems to have acted as a "leaky dam" against the rising mineralizing fluids. The largest part of the known ore usually has at least one wall of andradite, is within 1000 ft. of the intrusive contact and is associated with deep-cutting faults or fault dikes. The broad restriction of the ore to the vicinity of the intrusive contact is believed to be due to the crosscutting and generally broken character of the contact zone, and not necessarily to the presence of the exposed intrusive, for the sulfides and silicates are known to be younger than the solidification of exposed intrusive. This is shown by the fact that dikes that cut the intrusive are replaced by the silicates and localized silicates and ore.[5]

Silver-manganese-quartz Deposits below Impervious Beds in Southwestern New Mexico[6]

In southwestern New Mexico, within an area 45 miles in diameter—Santa Rita is the approximate center of it—there are seven mineral districts of striking similarity; namely, Chloride Flat and Boston Hill at Silver City, Lone Mountain, Georgetown, Cooks Peak, Lake Valley and Kingston. These were discovered and actively mined late in the nineteenth century, soon after the railroads reached the region. They were chiefly valuable for silver, but lead was important at Cooks Peak and Boston Hill, Chloride Flat and Lake Valley produced some silver-bearing manganese ore for flux. During the last decade Boston Hill produced large amounts of iron-manganese oxides for steel manufacture and, although now inactive, has large reserves.

These deposits appear to form a related series. They grade from an iron-manganese carbonate silver mineralization to a silver-lead type. Nearly all the minerals found in any one district are found in the others, and in every district but one the ore occurs beneath the Upper Devonian Percha shale. Except possibly at Lake Valley, a district the writer has not studied,[7] the ore is further localized by high-angle faults, fault-dikes, dike contacts and fractures, all of which cut the lower contact of the shale. The ore occurs as veinlike bodies, blankets, pipes, and chimneys (Figs. 4 and 5) in or near these crosscutting breaks in the lower Silurian Fusselman limestone and replaces the limestone and/or a siliceous breccia that occurs in places at the unconformity between the shale and limestone. The shoots seldom extend more than 100 ft. below this contact. All of

[5] Reference of footnote 3; 7.

[6] Reference of footnote 1; 62–67.

[7] Reference of footnote 1; 276–77.

the deposits have associated dikes and/or sills, generally intermediate in composition, except that at Lake Valley the only igneous rock is a post-ore andesite flow, which overlies the ore.

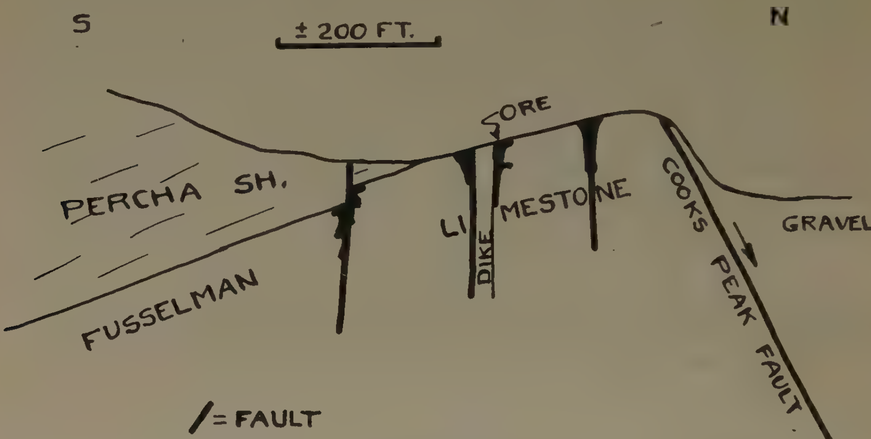

FIG. 4.—GEOLOGIC SECTION THROUGH SILVER DEPOSITS OF GEORGETOWN, NEW MEXICO.

From reconnaissance work by H. Schmitt. Diagrammatic and not drawn to scale.

In addition these deposits have significant *regional* structural and igneous associations. The Georgetown and Cooks Peak deposits are localized by fractures, faults and dike contacts which are auxiliary to the Cooks Peak fault (Fig. 6) and Boston Hill, Lone Mountain, Cooks Peak

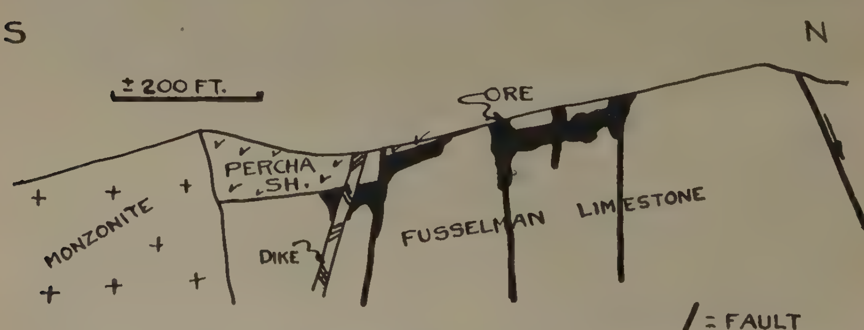

FIG. 5.—GEOLOGIC SECTION THROUGH BOSTON HILL IRON-MANGANESE DEPOSITS AT SILVER CITY, NEW MEXICO.

Based on detailed large-scale maps by H. Lary and H. Schmitt. The similarity of the structural control here and for the silver deposits represented by Fig. 4 should be noted. Diagrammatic and not drawn to scale.

and Kingston are near stocklike intrusives of intermediate composition. Boston Hill, Lone Mountain and Kingston are also near regional faults.

In a still broader way the southwestern New Mexico mineral subprovince, which is the most important of the state and of which these deposits are a part, is located at the junction of northwest-trending and

north-trending belts of folding and thrust faulting. Although mainly developed during the Laramide revolution, these belts seem to have been affected by late Tertiary folding, which possibly included minor thrust faulting. The northwest belt in Arizona may have been first deformed by the Jurasside[8] revolution.[9] These belts of repeated deformation are

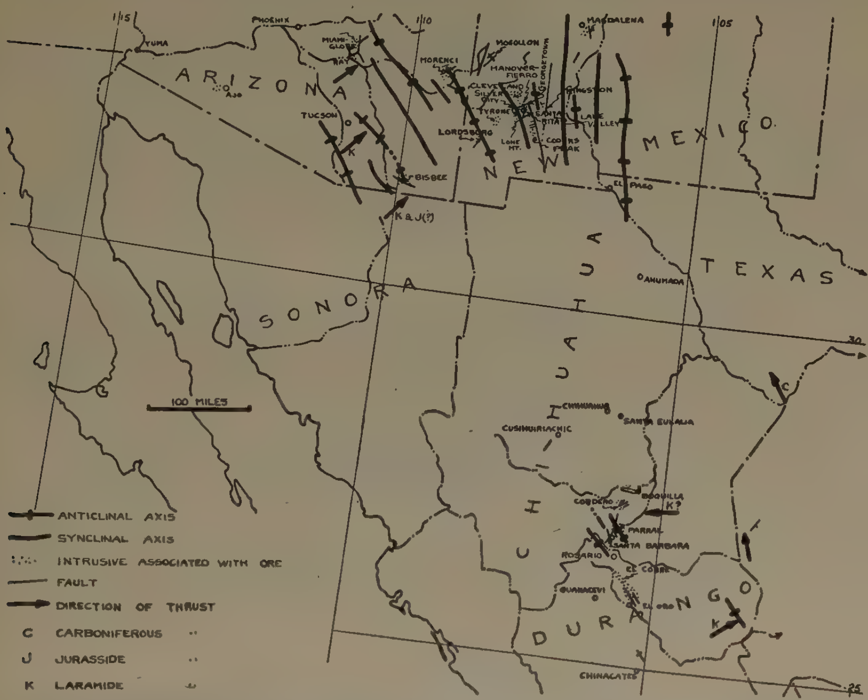

FIG. 6.—MAP OF NORTHERN MEXICO AND SOUTHERN ARIZONA AND NEW MEXICO, SHOWING LOCATION OF AREAS DESCRIBED IN THIS PAPER AND SOME ASSOCIATED FOLDS, FAULTS AND INTRUSIVES.

zones of especially thin pre-Eocene post-Algonkian sedimentary rocks.[9] Butler[10] believes they mark lines of change from thick to thin sedimentary rock. When the thicknesses of the pre-Eocene post-Algonkian sedimentary sections are plotted on a map in detail, however, the sedimentary sections appear to be much thinner along the belts than on either side of them.

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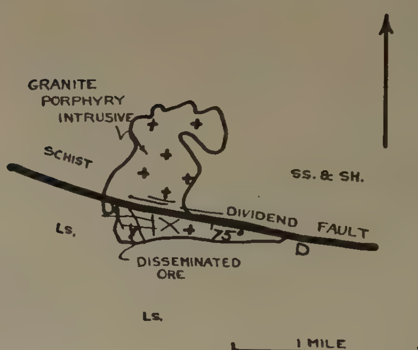
[8] Knopf's name for the late Jurassic or early Cretaceous revolution in the Sierra Nevada area [A. Knopf: Geology and Ore Deposits of the Rochester District, Nevada. U. S. Geol. Survey *Bull.* 762 (1924) 11].

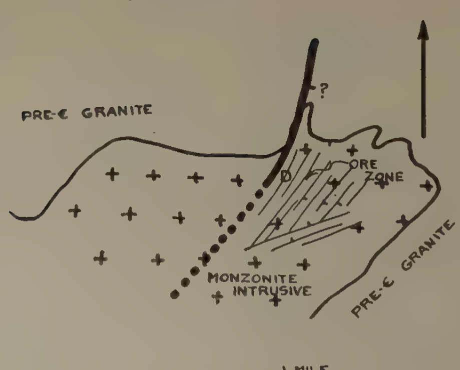
[9] H. Schmitt: An Outline of the Depositional, Tectonic and Erosional History of Arizona and New Mexico. In manuscript.

[10] B. S. Butler: Relation of Ore Deposits of the Southern Rocky Mountain Region to the Colorado Plateau. *Proc.* Colo. Sci. Soc. (1929) **12,** 23–36.

(A) FIERRO



(B) BISBEE



(C) TYRONE

Fig. 7.—Surface plans of intrusives and associated disseminated copper ore at Fierro and Tyrone, New Mexico and Bisbee, Arizona.

From maps by S. Paige, F. L. Ransome and H. Schmitt. Simplified and not drawn to scale.

Disseminated Copper Deposits at Fierro and Tyrone, New Mexico, and Bisbee, Arizona

There are many of the so-called disseminated copper deposits in the province under discussion, and those studied by the writer include Hanover Mountain at Fierro, Tyrone and Bisbee. The first never was operated as a disseminated deposit, but produced a small amount of ore from fissures; the second and third are closed down. The localization at Hanover Mountain (Fig. 7*a*) is governed by a master fault, which cuts the edge and dips away from the Fierro-Hanover intrusive granodiorite "stock." The ore mined to date was the richer of the supergene enriched material localized by fissures and faults in brecciated Colorado sandstone and shale in the hanging wall of the Barringer fault. The lower grade, more widely disseminated supergene enriched material has not yet been exploited, probably because of the small visible tonnage and low grade. An adjacent part of the "stock," also in the hanging wall, is broken and mineralized with quartz and sericite but not with copper minerals.

The disseminated copper ore at Bisbee, Ariz. (Fig. 7*b*) is associated with similar structural conditions; that is, it lies in the hanging wall of the Dividend fault where the latter cuts the Sacramento Hill intrusive porphyry. At Tyrone (Fig. 7*c*) the ore also lies in the brecciated down-faulted wall of a master fault and, as at Hanover Mountain, only the richer ore localized by fissures, faults and breccia masses has been exploited.[11]

Cleveland, New Mexico

The Cleveland zinc and copper mine is N. 10 E. 6 miles from Silver City, N. M., and 2 miles west of Pinos Altos. A roof pendant of Upper Devonian shale, Carboniferous limestone and shale and Upper Cretaceous quartzite and shale lies in intrusive granodiorite (?) porphyry of late Upper Cretaceous(?) age.[12] The ore replaces Carboniferous thin, pure limestone beds intercalated with minor shale and in detail appears to be further localized by the intersection of a high-angle normal fault with a steeply dipping granodiorite (?) porphyry dike (Fig. 8), which is an apophysis from a large mass of similar intrusive below as determined by diamond-drilling. The intersection appears to have guided the metal-bearing fluids to the favorable limestone beds where replacement took

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[11] S. Paige: Reference of footnote 2; 15–16.
Also The Tyrone District, New Mexico. U. S. Geol. Survey *Prof. Paper* 122 (1922) 16–19.

[12] Areal geology map in reference of footnote 2; also S. Paige: The Ore Deposits near Pinos Altos, New Mexico. U. S. Geol. Survey, *Bull.* 410 (1910) 109–30.

place, possibly influenced by the chemical character of the purer beds and/or possibly by their coarser grain.[13]

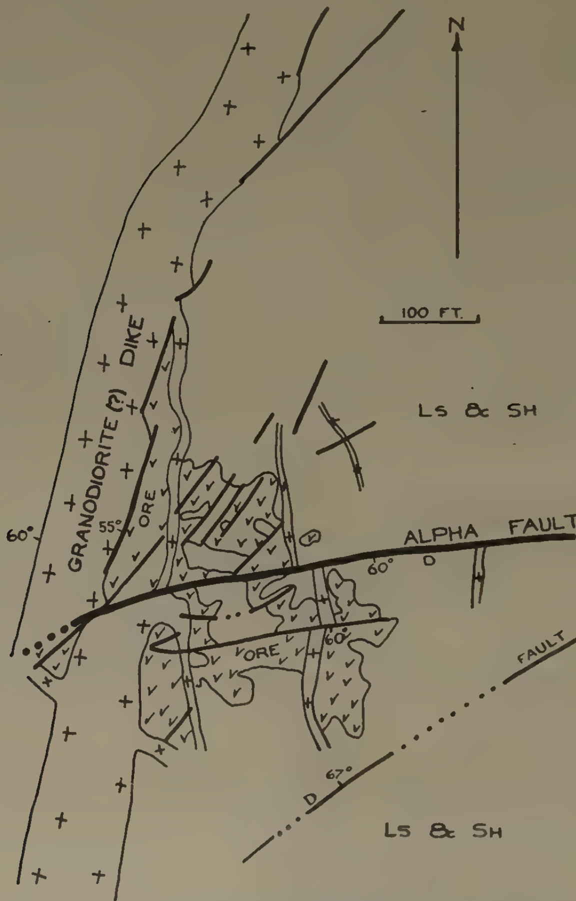

FIG. 8.—GEOLOGIC PLAN SHOWING RELATIONS ON TUNNEL LEVEL OF CLEVELAND MINE, NEW MEXICO.
From maps by C. F. Park, O. N. Rove and H. Schmitt. Drawn to scale.

NITT MINE, MAGDALENA DISTRICT, NEW MEXICO[14]

The Nitt mine is on the north end of the principal mineralized zone at Magdalena, N. M., in a reentrant of a monzonite (?) intrusive contact.

[13] It has been noted that the coarse-grained pure limestone or dolomite beds so generally associated with limestone replacement ore have intercrystal capillary openings easily penetrated by liquids and gases. They are weak rocks, and doubtless small unbalanced stresses under conditions that permit increase in volume make them more porous by a slight rotation of the crystals, although when subjected to sufficient confining and differential pressure they flow and recrystallize.

[14] Reference of footnote 1; 241, 258; also G. F. Loughlin, A. H. Koshmann, S. G. Lasky and V. T. Stringfield: Geology and Ore Deposits of the Magdalena District,

It produced copper, zinc and zinc-lead ore, which was localized by, and which replaced, coarse, pure, lower Mississippian limestone. Auxiliary faults in the hanging wall of a master fault (Figs. 9 and 10) cut the limestone and further localized the ore. The mine is of interest to geologists

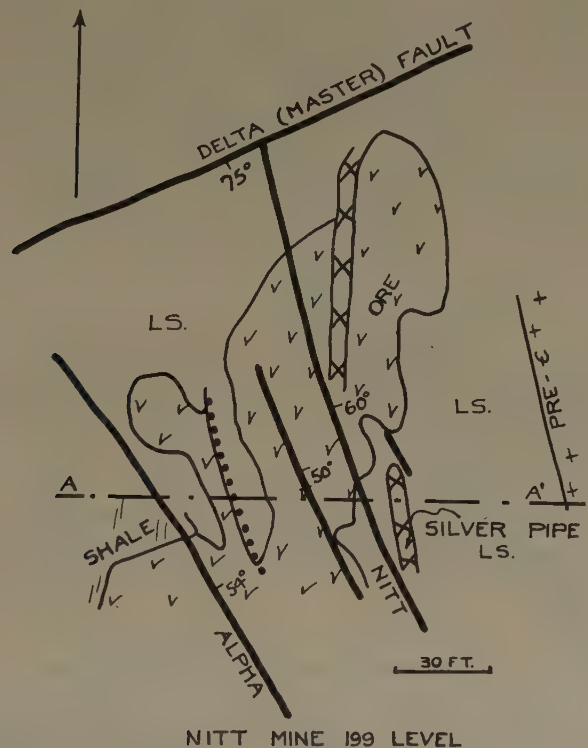

Fig. 9.—Geologic plan of 199-ft. level of Nitt mine, Magdalena district, New Mexico.
Simplified reproduction of an original map by H. Schmitt. Drawn to scale.

chiefly for its complicated fault system, which, however, is easily worked out by mapping the numerous key beds.

Santa Barbara, Chihuahua[15]

The country rock at Santa Barbara is thin-bedded shaly limestone and shale (Santa Barbara series), which has been closely folded with strong overthrust from the east. The ore is found in high-angle normal faults, which are later than the folding and form a system of linked veins

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New Mexico. New Mexico Bur. Mines and Mineral Resources, *Bulletin* in preparation.

[15] J. E. Spurr: The Ore Magmas, 669–74. New York, 1923. McGraw-Hill Book Co. H. Schmitt: Geologic Notes on the Santa Barbara Area. *Eng. & Min. Jnl.* (1928) **126**, 407–411.

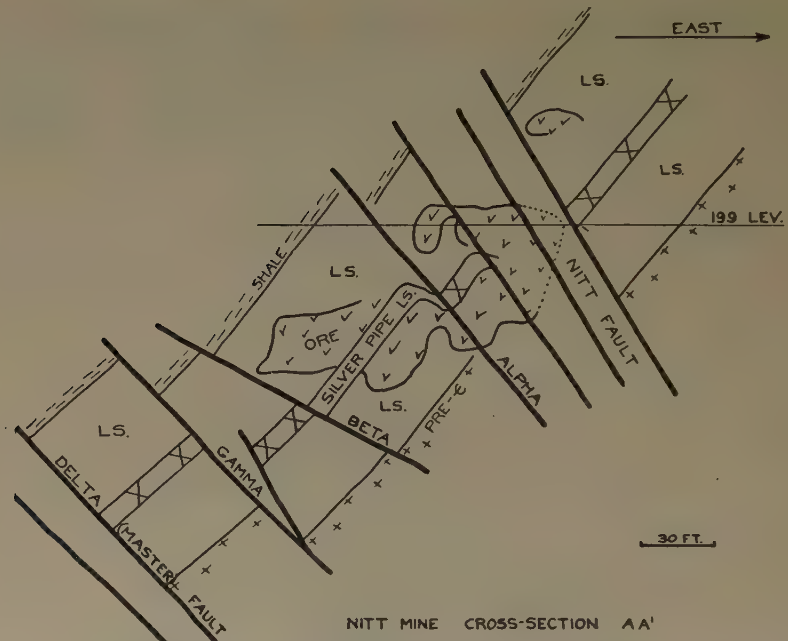

FIG. 10.—GEOLOGIC SECTION THROUGH NITT MINE, MAGDALENA DISTRICT, NEW MEXICO (SEE FIG. 9 FOR LOCATION).
Reproduction of a section by H. Schmitt. Drawn to scale.

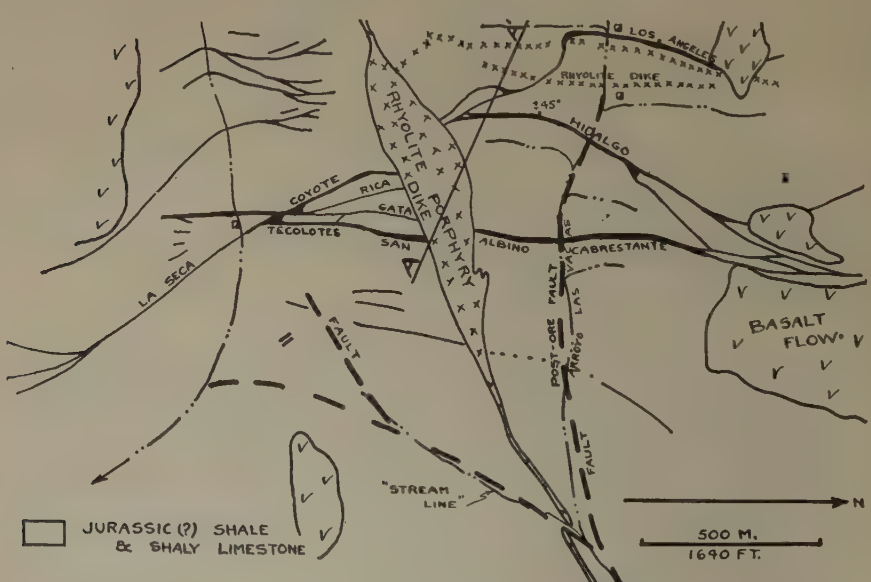

FIG. 11.—GEOLOGIC SURFACE MAP OF PART OF SANTA BARBARA DISTRICT, CHIHUAHUA.
Reproduction of a map by J. Barry. Drawn to scale.

(Fig. 11). Vertical sections show similar linking. Only one "crossing" is known. The ore does not form distinct shoots as a rule, but follows the faults as continuous tabular veins with strike lengths of more than a kilometer in several instances. The richest and thickest parts of the veins, however, are at vein junctions.

The structural relations at Santa Barbara are of the simplest type. The intricate folded structure of the country rock is not known to have influenced the localization of ore. Horsetailing and pre-ore (?) faults are criteria for the boundaries of the shoots or veins. Thick hypogene enriched sections with a low angle of pitch suggest hanging-wall or foot-wall branchings, which if not watched for may be overlooked when stoping.

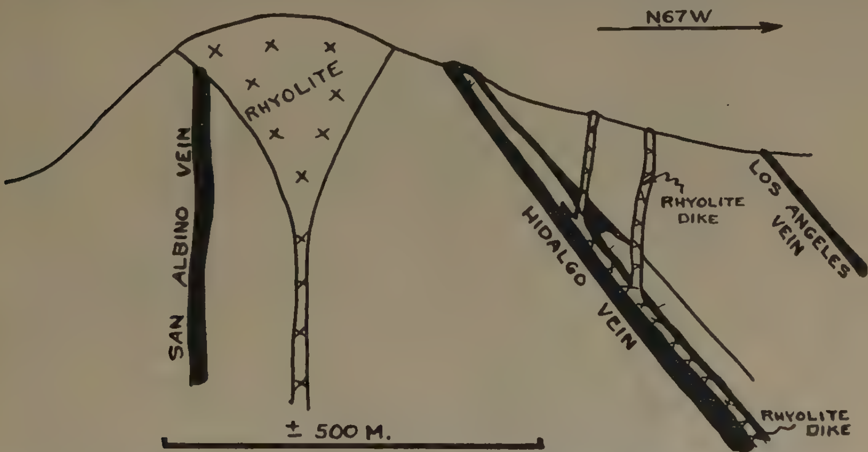

FIG. 12.—GEOLOGIC SECTION THROUGH SAN ALBINO, HIDALGO AND LOS ANGELES VEINS, AT SANTA BARBARA, CHIHUAHUA (SEE FIG. 11 FOR LOCATION). Sketched from sections by H. Schmitt. Not drawn to scale.

The rhyolite dike, which widens rapidly upward (Fig. 12), seems to mark the hot center of the district if the zoning of minerals[16] around it is a criterion. It may have been a volcanic vent, but is younger than the ore. No pre-ore coarse-grained intrusives are known to be near by. One of the fault veins (the Hidalgo vein at Santa Barbara) with which linked branches are associated extends north to San Francisco del Oro, a distance of more than 4 km. (2.5 miles). The Alfareña vein with its extensions is more than 6 km. (3.7 miles) long.

PARRAL DISTRICT, CHIHUAHUA[17]

There are three classes of country rock in the Parral district; intrusive monzonite; volcanic flows, tuffs and breccias; and sedimentary shale and

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[16] Schmitt: Reference of footnote 15, 269.

[17] H. Schmitt: Geology of the Parral Area. *Trans.* A.I.M.E. (1931) 268–89. H. E. McKinstry: Discussion. *Idem.*, 289–90.

shaly limestone. The last resembles and is doubtless equivalent to the Santa Barbara series. Each of these classes of rock behaves distinctively when faulted and fractured, and so each encloses correspondingly distinctive veins and oreshoots. The fault veins[18] are linked (Fig. 13)

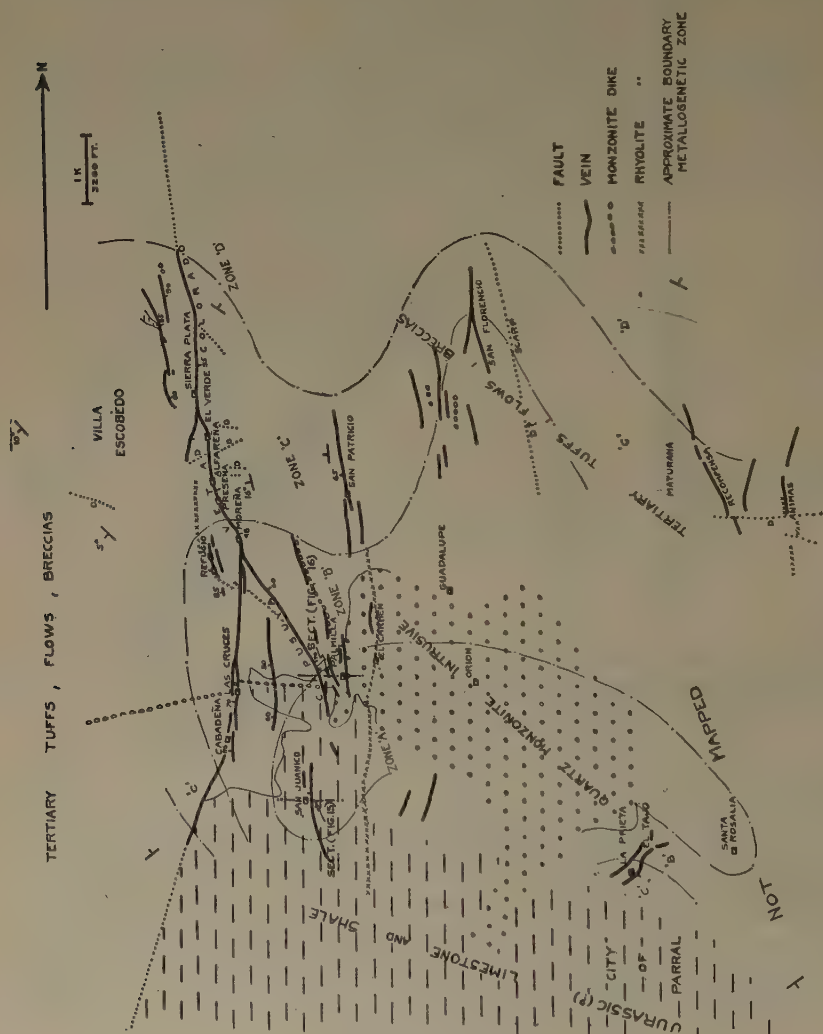

Fig. 13.—Geologic plan of part of Parral district, Chihuahua. Reproduced from maps by Rogers, Mayer and Ball (1921) and H. Schmitt (1925). Drawn to scale.

as at Santa Barbara. The writer knows of no vein "crossing" in the district. This system of veins is directly in line with the Alfareña vein at

[18] The writer prefers the term fault-vein to fissure-vein because the latter has been loosely used. Other useful terms include: fracture-vein for veins without offset, fault-dike for associated dike and fault and even fault-dike-vein to express a common association.

Santa Barbara and may connect with it beneath the intervening valley fill. The Veta Colorado, which is the principal vein of the district, is also a normal fault with a measured offset of 450 m. (1450 ft.) at one place. It has a known strike extension of 8 km. (5 miles). The oreshoots are more restricted than at Santa Barbara; that is, their boundaries along the strike of the veins are sharp and individual shoots are separated by long barren intershoot stretches. On the larger veins, however, the small strike extension of the shoots is compensated in terms of volume by greater width.

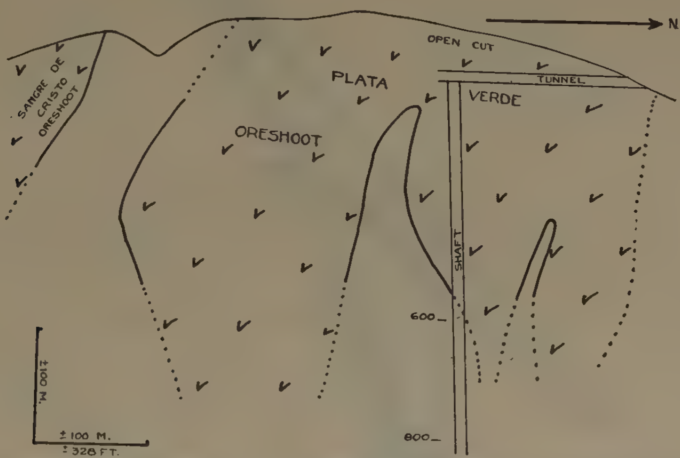

Fig. 14.—Longitudinal vertical projection of oreshoots of Plata Verde mine, Parral district, Chihuahua.

The part above the 600-ft. level was sketched from maps by H. Schmitt, that below from verbal descriptions. Not drawn closely to scale.

The oreshoots of the district show four or five types of form and structural association:

1. The oreshoots in the fault veins which cut the volcanic rocks are of a simple tabular form, V-shaped, and bottom in small unminable roots (Fig. 14 and Figs. 8 and 9 in reference of footnote 17). Two of the largest shoots along the Veta Colorado, the Plata Verde and Sierra Plata—the only ones mapped in detail by the writer—appear to be localized by breccia-filled depressions in the footwall of the Veta Colorado fault.[19] Wandke and Martinez[20] noted similar associations at Guanajuato. The ore deposits of these two districts resemble each other in other ways.

2. In the thin-bedded, brittle, shaly limestone and shale the fault veins have many unsystematic footwall and hanging-wall branches like those in the same rock at Santa Barbara. The San Juanico group of

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[19] Reference of footnote 17, 286.

[20] A. Wandke and J. Martinez: The Guanajuato Mining District, Guanajuato, Mexico. *Econ. Geol.* (1928), **23**, 32.

veins and oreshoots in the southwestern part of the district is a good example of this type (Fig. 15).

3. Where the Veta Colorado fault vein cuts the edge of the intrusive monzonite (Fig. 16) there occurs a system of veins and oreshoots in the monzonite which resembles the Comstock lode,[21,22] but on a smaller scale.

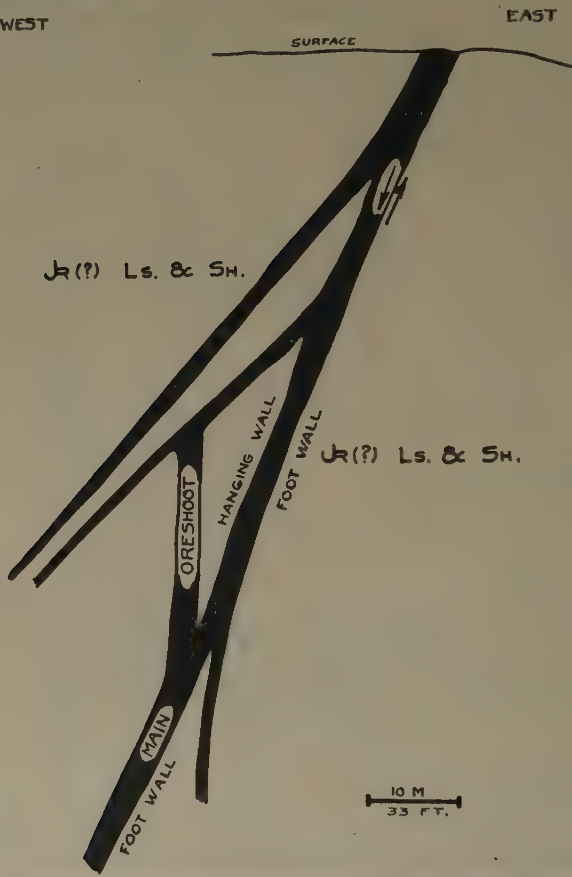

FIG. 15.—GEOLOGIC CROSS-SECTION OF SAN JUANICO VEIN, PARRAL DISTRICT, CHIHUAHUA (SEE FIG. 13 FOR LOCATION).

Exact reproduction of an original section by H. Schmitt. Both walls are intricately folded and faulted thin-bedded limestone and shale.

A footwall master fault vein has developed hanging-wall tension fracture veins along which a podlike or thick lenslike orebody has been localized. Augustus Locke, in a conversation with the writer, remarked that its shape, size and attitude suggests growth by mineralization stoping;[23]

[21] G. F. Becker: U. S. Geol. Survey *Monograph* 3 (1882).

[22] W. Lindgren: Mineral Deposits, 570. New York, 1928. McGraw-Hill Book Co.

[23] A. Locke: The Formation of Certain Orebodies by Mineralization Stoping. *Econ. Geol.* (1926) **21,** 431–53. Discussion, P. A. Wagner: *Ibid.* (1927) **22,** 740–741.

and, indeed, coarse ore breccia such as may have resulted from natural stoping occurs in it. It may be significant that the Virginia City occurrence was developed in massive intrusive rock of intermediate composition and a somewhat similar pod or chimney in monzonite makes the ore of the Cactus mine.[24]

4. Rogers, Mayer and Ball in a private report to the Cia. Consolidacion Minera de Parral noted that in the Palmilla mine area the veins

Fig. 16.—Geologic cross-section of Palmilla and associated veins, Parral district, Chihuahua (see Fig. 13 for location).

Reproduction of an original section by Rogers, Mayer and Ball with minor additions by H. Schmitt. Drawn to scale.

were linked, never crossed, and the vein junctions localized oreshoots. McKinstry[25] emphasized the influence of vein junctions on oreshoot localization in the San Patricio vein and in others east of Parral.

5. Hulin[26] suggests that the Prieta oreshoot resulted from stretching by a cross fault, but the plan of the sixth level of the Prieta-Tajo mines

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[24] B. S. Butler: Geology and Ore Deposits of the San Francisco Region, Utah. U. S. Geol. Survey *Prof. Paper* 80 (1913) 174.

[25] Reference of footnote 17, 290.

[26] C. D. Hulin: Structural Control of Ore Deposition. *Econ. Geol.* (1929) **24**, 15–49. Discussion, F. R. Koeberlin: *Idem.*, 657–63; C. A. Porter, 866–69.

shows a continuous vein from one end to the other with no thickening or offset near a cross fault, as he shows in his plan of the surface.

Cordero (San Juan), Chihuahua

The silver-lead district of Cordero (San Juan), Chihuahua, is N.17E 35 km. (22 miles) from Parral and produced rich silver-lead ore for a few years just preceding 1900, when it was abandoned. A rhyolite porphyry "stock" about one kilometer in diameter (Fig. 17), with a few satellitic irregular masses and dikes of the same rock, has intruded widely silicified and slightly garnetized and epidotized thin-bedded shaly limestone and shale of the Santa Barbara series, which, as at Santa Barbara, has been closely folded and overthrust from the east. Fault veins, bearing north-

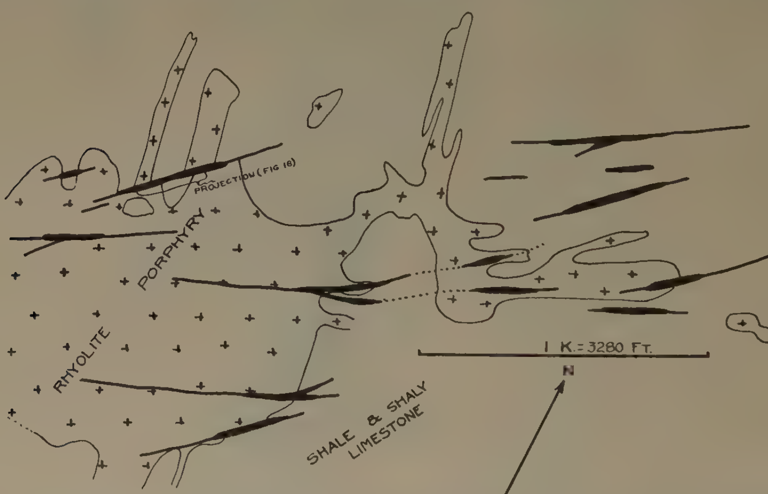

Fig. 17.—Geologic plan of central and eastern part of the Cordero (San Juan) district, Chihuahua.

Sketched from the original map (R. F. = 1/2500) by H. Schmitt. Not drawn to scale.

east and seldom more than one meter wide, in general parallel with few branches and no crossings, cut the sedimentary and intrusive rocks. The vein linkage so prominent in the Santa Barbara and Parral districts is lacking.

The oreshoots are localized at the contact of the rhyolite with the sedimentary rocks. Indeed, no commercial ore is known to extend over 150 m. (480 ft.) into the rhyolite (Fig. 17) and probably none extends farther than this into the limestone, because where the veins are wholly in the sedimentary rock they are accompanied by widespread silicification, which is an indication of near-by intrusive rhyolite in this district. Why should the ore be localized at the contact only? Is it because, strictly speaking, this contact is literally a fault whose intersections with

the fault veins formed crossings that localized ore for purely mechanical reasons, or is it because during the sulfide mineralization there was a sharp chemical and heat unconformity along the contact in spite of the fact that the intrusive had already solidified? Possibly all three factors were cooperant. The walls of oreshoots are rhyolite, limestone, or

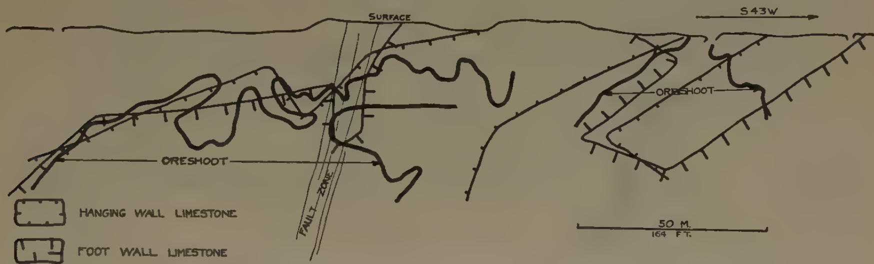

Fig. 18.—Longitudinal vertical projection of La Luz vein, Cordero (San Juan) district, Chihuahua (see Fig. 17 for location).

Drawn to scale from maps by H. Schmitt. In several places the offset of the hanging-wall and footwall patterns of rock shows the direction and amount of fault movement. The vein dips toward the front of the section.

rhyolite opposite limestone, and the best ore is found where both walls are limestone, but still near intrusive rock (Fig. 18).

The situation at Cordero is suggestive of a volcanic and mineralization center[27,28] similar to Parral[29] and Santa Barbara (p. 12). The fine-grained groundmass of the rhyolite porphyry suggests shallow intrusion.

El Cobre, Durango

The El Cobre prospects are about 40 km. (25 miles) southeast of Rosario, Durango, on Arroyo Sardinas, which flows southward into Rio El Oro-Nazas. An unusually pure limestone conglomerate[30] more than 150 m. (500 ft.) thick capped by rhyolite tuffs and flows is intruded by binary granite (granitelle) which is oval in plan, 1.5 by 1.0 km. (1.0 by 0.6 miles) with the long axis northwest. The conglomerate and volcanic rocks dip northeast and southwest from the granite, giving, as a result, a northwest anticline whose axial location and trend are similar to those of the granite (Fig. 19). The limestone conglomerate adjacent to the granite, particularly the roof pendant (Fig. 19), has been completely replaced by jasperoid without shrinkage, for the pebbles and boulders are

[27] P. Niggli: Ore Deposits of Magmatic Origin. T. Murby & Co., London. Translation by H. C. Boydell.

[28] G. Berg: Zonal Distribution of Ore Deposits in Central Europe. *Econ. Geol.* (1927) **22**, 113–32.

[29] Reference of footnote 17, 270.

[30] Probably of post-Cretaceous and pre-Tertiary volcanism age, for it is made of the gull-gray Cretaceous (?) limestone boulders and contains no fragments of volcanic rocks. It extends for at least 35 km. (15 miles) southeast on the northeast side of the valley of the El Oro-Nazas River.

the same size whether silicified or not. Minor tourmaline has been introduced into the rhyolite. No garnet was seen macroscopically or microscopically and the only iron introduced occurs in sulfides, red jasperoid and minor siderite. A few weakly mineralized fissures occur in the

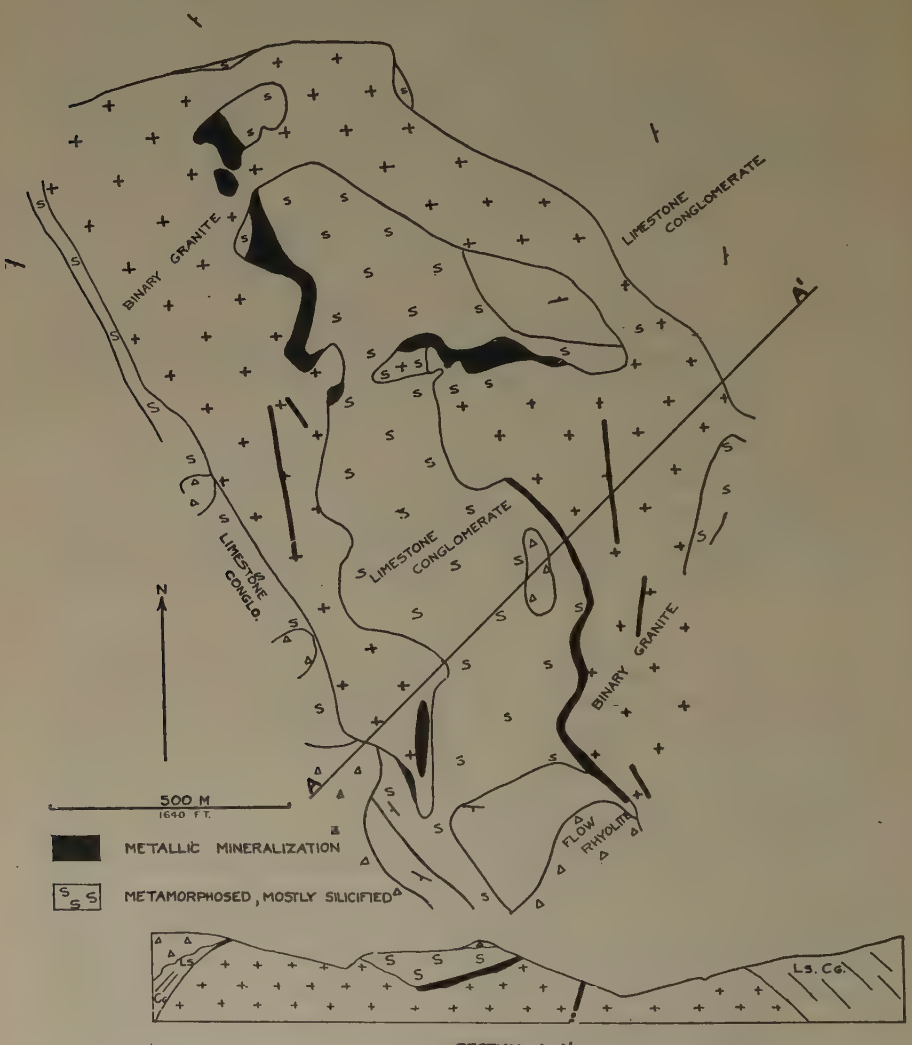

Fig. 19.—Geologic plan and section of El Cobre, Durango, copper district. Simplified reproduction of a map by H. Schmitt. Drawn to scale.

granite, but most of the exposed metallic mineralization is composed of sulfides, chiefly copper and iron, or their oxidized products, in places chiefly native copper, which occur as a continuous blanket at the immediate contact of jasperoidized limestone with intrusive. This blanket

averages 1.5 m. (5 ft.) thick and at a few places contains up to 3.0 per cent copper.

The metallic mineralization is largely limited to the roof pendant or to near-by fissures, and its intensity appears to be roughly inversely proportional to the dip of the contacts. The blanket form is possibly the result of closely localized brecciation or fracturing at the contact promoted by the change in the structure and physical character of the rocks. Any pronounced temperature unconformity had doubtless disappeared at the immediate contact when the sulfides came in, for the magma had been solid and losing heat for some time, and if the silicification was presulfide there was no appreciable chemical unconformity because the silicified limestone conglomerate and granite have no large difference in composition, and indeed, the granite is silicified at the contact in places.

Conclusions

A review of the structural associations of certain orebodies and districts in the Southwest subcontinental area, excepting the manto-chimney deposit, suggests several conclusions:

1. Districts tend to be associated with:
   - (*a*) Volcanic-intrusive centers (see reference of footnote 22, 529), and/or
   - (*b*) Regional faults with a strike length of more than 5 miles and/or
   - (*c*) Linked fault-fracture systems, and
   - (*d*) Folded and thrust-faulted belts, which were localized along zones of thin sedimentary rocks that underwent several widely separated periods of deformation.
2. Oreshoots tend to be associated with:
   - (*a*) The junctions of veins.
   - (*b*) Pods and irregular masses of breccia and auxiliary and sympathetic fractures and faults in the hanging walls of master faults.
   - (*c*) The intersections of crosscutting structural features such as high-angle faults, fractures, dikes, and contacts of "stocks" with the contact of relatively impervious beds, especially shales and subjacent, pure, coarse-grained limestones or dolomites, and/or
   - (*d*) The intersection of crosscutting structural features with other crosscutting structural features; *i.e.*, "crossings."[31]

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[31] The writer's experience in the province under discussion has brought him in contact with but few cases of oreshoot association with the intersections of veins, faults and fractures. Such localization is doubtless more important than the data given in this paper would indicate. In certain districts outside this area it is of predominating importance.

(*e*) Breccia zones in master faults, including breccia-filled depressions in the footwall.

(*f*) The immediate contact of intrusives with wall rocks, particularly when brecciated, and/or when intersected by faults and fractures.

(*g*) The outer edge of contact pyrometasomatic zones when brecciated and/or intersected by faults and dikes.

3. The following types of structural associations with oreshoots are rare:

(*a*) Gently flexed anticlines and synclines in association with an impervious bed and a subjacent bed favorable to replacement.

(*b*) Intersection of a dip change in the wall rock with a high-angle dike-fault, a bed favorable to replacement and a superjacent shale bed.

(*c*) Intersection of a flat thrust fault with a high-angle normal fault,[32] a bed favorable to replacement and an overlying shale bed.

(*d*) Intersection of a dike-fault or fault with a favorable bed—no impervious bed above.

In one case a mineral subprovince is associated with the junction of two folded belts (p. 5).

The subordinate place taken by anticlines as a factor in localization should be noted. The writer has seen only two cases of anticlinal association in this province, but at Tombstone, Ariz., the ore occurs in anticlines (Emmons, after Church)[33] and anticline-ore association is said to be found at Kingston, New Mexico. The Santa Eulalia manto-chimney is associated with a low arch.[34]

General Comment

Although the possible contributing factors in the localization of ore other than structural features, such as temperature and pressure variations, chemical changes and position relative to the source have been discussed only incidentally, nevertheless the universal association of the ore deposits of this province with sharp or localized features of structure supports a theory of occurrence in which the influence of such features is given first place. Preparation of the ground—that is, breaking and

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[32] The intersection of flat thrust faults with high-angle faults and fractures is especially important in several districts outside the area under discussion. Good examples are known at Goodsprings, Nevada [D. F. Hewett: Geology and Ore Deposits of the Goodsprings Quadrangle, Nevada. U. S. Geol. Survey *Prof. Paper* 162 (1931).], and the Cottonwood-American Fork district in Utah [B. S. Butler: Ore Deposits of Utah. U. S. Geol. Survey *Prof. Paper* 111 (1920).].

[33] W. H. Emmons: The Principles of Economic Geology, 203. New York, 1918. McGraw-Hill Book Co.

[34] John Barry, oral communication.

brecciation—is considered essential. Temperature doubtless has important influence in the separation and classification of the elements; the importance of chemical reactions with the wall rock is debatable; the influence of pressure, although minimized, must be considered where critical phenomena exist; the position of ore relative to the source hinges upon theories of the location of the source. But the need of an opening to start with cannot be escaped.[35,36,37] Furthermore, judging from the conditions in the province just reviewed, this opening must connect with the depths of the earth's crust by a crosscutting break such as a high-angle fault, dike, breccia cone or chimney or a deep-cutting stock, neck or other igneous form.

A theory of occurrence that emphasizes ground preparation explains why ore deposits are limited to the first mile or two of the earth's crust, for the volume of the broken ground in many mineralized areas appears to diminish with the depth, as a cone whose sides converge at, say, 45°. Many have been impressed by the rapid downward diminution in the size of orebodies, of brecciated rock and the tendency for fissures, faults and dikes to focus in depth (Figs. 12 and 16, and the Comstock lode cross-section in reference 22, p. 570). In places where deep development has been done, many of the so-called stocks are seen to narrow to a focus also; that is, have the form of a funnel. Billingsley and Locke show that intrusives in Utah and Nevada stocklike near the surface pinch in depth.[38] In several districts the writer is familiar with, Parral (Fig. 16), Hanover (Fig. 2) and Santa Barbara (Fig. 12), the dips of the explored contacts suggest such a structure. The Goldfield, Nevada, intrusive dacite would have been called a stock if deep development had not been done. Field work by Ransome, Locke and others shows that it narrows down to a 5-ft. dike at about 800 ft. below the surface. In other words, some "stocks" behave like ore; *i. e.*, they tend to constrict downward in the first 1000 ft. or so of the earth's crust.

The theory that most "stocks" are truncated cupolas of batholiths has become so firmly established that it is heresy, perhaps, to suggest that the probabilities are good that many "stocks" with which contact pyrometasomatic deposits are associated in the province under review and in adjoining areas have "floors." If such a condition is verified the current theory for the origin of the contact pyrometasomatic and associated ore deposits will need revision for this province at least. There is already a large body of evidence showing that the deposition of many of the con-

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[35] A. Locke: The Opening as a Reason for Ore. *Econ. Geol.* (1928) **23**, 93–8. Discussion, Dougherty: *Ibid.*, 569–78.

[36] Reference of footnote 26.

[37] G. W. Bain: Structure of Gold-bearing Quartz in Northern Ontario and Quebec. A. I. M. E. *Tech. Paper* 327 (1930).

[38] P. Billingsley and A. Locke: A. I. M. E. *Tech. Pub.* 501 (1933).

tact pyrometasomatic deposits in western United States was later than the consolidation of the adjacent exposed intrusives and if these intrusives are not the cupolas of batholiths the question of the source of the mineralizing fluids seems even more complicated than current theory suggests.

It seems likely that the primary factor in the localization and association of "stocks," contact pyrometasomatism and ores, is a deep-cutting break of one sort or another in the earth's crust, that the contact pyrometasomatic deposits are not derived from the "stocks" but that their association is the result of localization along mutual outlets to the earth's surface.[39]

In conclusion, it is perhaps significant that mining geologists whose living depends on their success in applying geology, and especially those who have had good success in finding ore, continually emphasize the importance of studies of structure in solving the problems of ore occurrence, particularly the careful measurement of the rocks by large-scale methods of mapping. The successful application mining geology in the past has been largely the result of such work. The writer believes, however, that specialized studies of outcrops and the less obvious surface expressions of ore, the alteration jackets or halos of orebodies, vertical zoning, oreshoot extension and the character of the roots and branches[40] of orebodies will have a proportionately greater success in the search for ore in the future.

Acknowledgments

The writer is indebted to F. F. Grout and Augustus Locke for criticism of the manuscript of this paper.

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[39] A. C. Spencer [U. S. Geol. Survey *Prof. Paper* 96 (1917).] has expressed this idea for the Ely, Nev., deposits, and that the primary source for the magmas and ores was deep seated.

[40] A term here suggested for the material, not ore, or the effects left along the outlet path of the fluids that made the orebodies, to be used in conjunction with the term "root" now fairly well established.

Tectonic Position of Ore Districts in the Rocky Mountain Region

By Paul Billingsley,* and Augustus Locke,† Members A.I.M.E.

(New York Meeting, February, 1933)

The mining districts of the first order[1] of the western United States (and borders) are those named on Fig. 1. These fall into four groups: (1) in the eastern outliers of the Rocky Mountain system; (2) in the Rocky Mountain system itself; (3) in the Great Basin; and (4) in the Sierras and Coast ranges. Of these four groups, the first three are almost entirely of Tertiary age and are within a belt of compressive folding which we shall call the Rocky Mountain-Great Basin thrust arc. The backbone of this belt is shown by the line *BAC*.

The position of the ore districts in this belt indicates a conformance to linear elements of the continental pattern. These are additional to the peripheral elements emphasized by Butler.[2]

Nature of the Thrust Arc

The thrust arc separates regions of contrasted kinds. To the east of it are flat-lying plateaus interrupted by earlier mountain folds; to the west, sunken basins, in which block-faulted ranges lie like an anchored fleet in a sea of desert wash or lava. The cross-sections are as shown in Fig. 2.

The backbone of the belt is the upward and eastward moving block represented by the Glacier Park, the Wasatch, and the Virgin mountains, successively. The structure represented on these sections is the culmination of events which began far back in geologic time and throughout which a contrast has existed between the regions east and west of the backbone line. Before the Pennsylvanian, as Fig. 3 shows, there was a shallow shelf on the east and a deep marine trough on the west; after

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† Consulting Geologist, San Francisco, Calif.

[1] In the first order are included those with a gross output worth $200,000,000 or more; in the second order those from $50,000,000 to $200,000,000; and in the third order those from $10,000,000 to $50,000,000.

[2] B. S. Butler: Relation of the Ore Deposits of the Southern Rocky Mountain Region to the Colorado Plateau. *Proc.* Colorado Scientific Soc. (1929) **12,** 23–36.

that time, there have been, with minor interruptions, uplift and erosion on the west, and heavy, arid, continental sedimentation on the east.

The correlation of these reversed conditions with the backbone line appears on Fig. 4, which shows the thrust arc coinciding closely with the

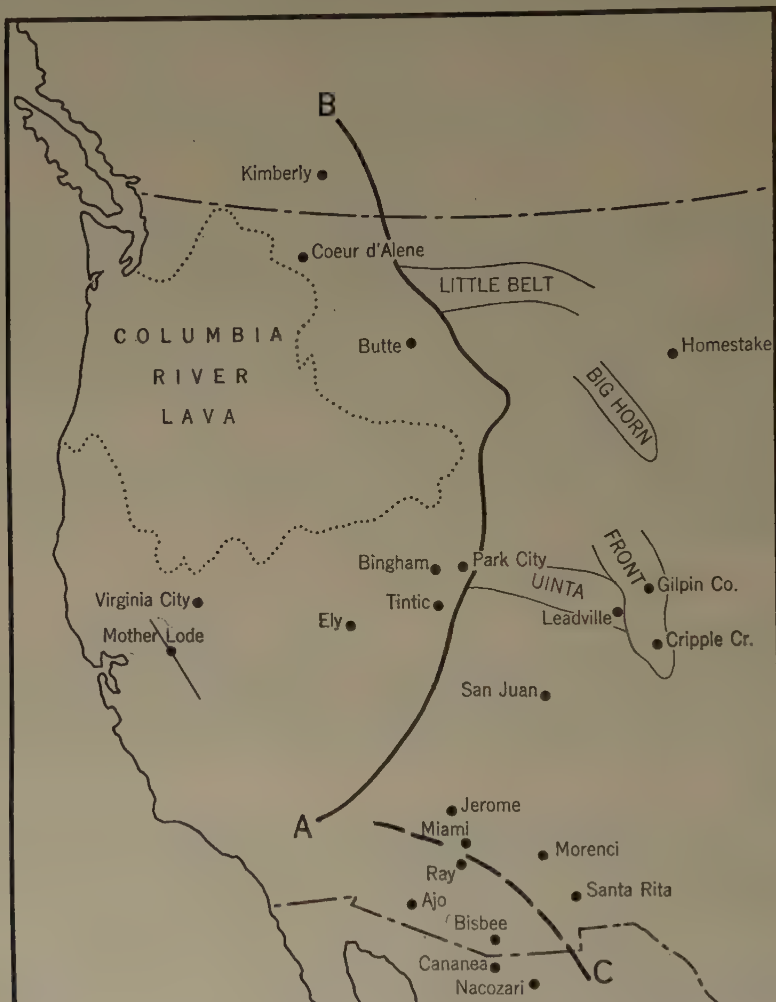

FIG. 1.—PRINCIPAL MINING DISTRICTS OF WESTERN UNITED STATES.

eastern edge of the Algonkian and lower Paleozoic basins, and also with the western foci of the post-Pennsylvanian continental fans.

A final contrast lies in the presence, east of the thrust arc, of festooned folds of open anticlinal structure. These include the Little Belt-Snowy Mountain axis in Montana; the Big Horn-Owl Creek axis in Wyoming;

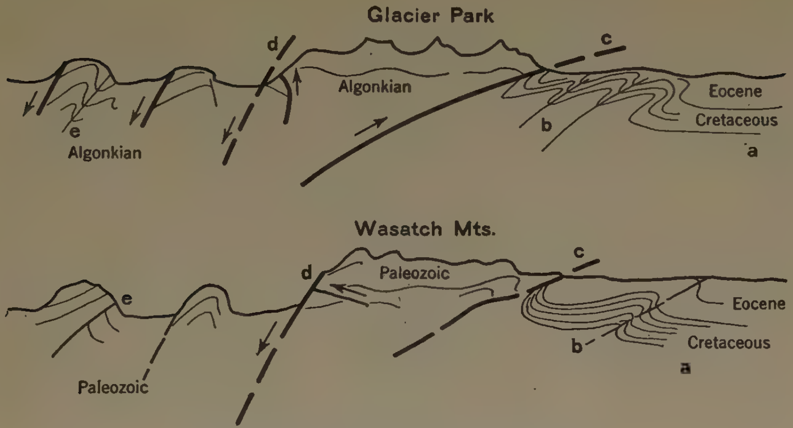

Fig. 2.—Sections across thrust belt.

Montana (Upper Section)

a. Flat beds on plains.
b. Minor thrusts; Cut Bank, etc.
c. Lewis overthrust.
d. Mission Range normal fault.
e. Minor thrusts.

North Utah-Wyoming (Lower Section)

a. Flat beds, Green River area.
b. Minor thrusts; Coalville, etc.
c. Absaroka, etc. thrust.
d. Wasatch normal fault.
e. Stansbury thrust.

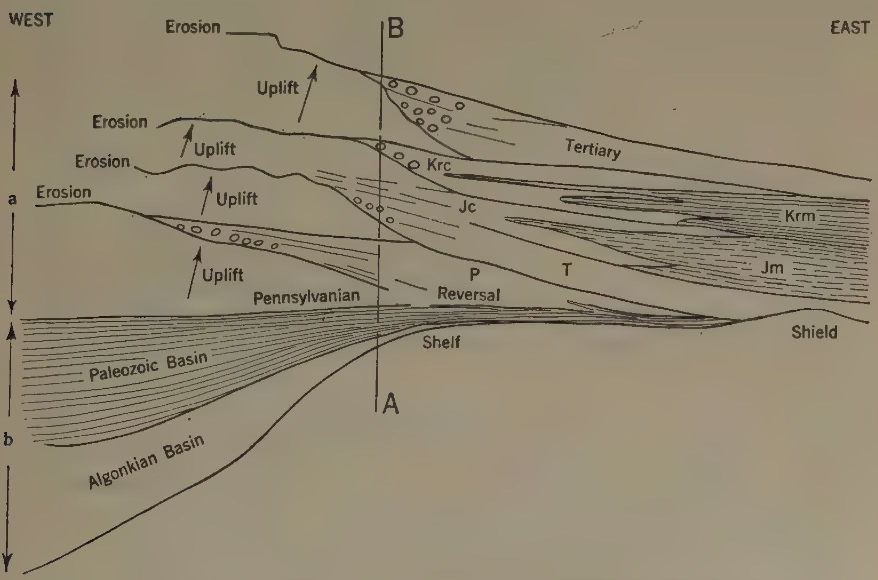

Fig. 3.—Post-Pennsylvanian reversal of sedimentation shown diagrammatically.

Krc. Cretaceous fans.
Krm. Cretaceous marine from gulf.
Jc. Jurassic fans.
Jm. Jurassic marine from gulf.
T. Triassic fans.
P. Pennsylvanian fan and delta.
A-B. Position of thrust arc along line of demarcation between: (*a*) later western uplifts and eastern deposits; (*b*) Paleozoic western basin and eastern shelf.

the Rock Springs dome in Wyoming; the Uinta axis in Utah and Colorado; the San Rafael, Torrey and Kaibab axes in Southern Utah; and the many northwest anticlinal folds of southeastern Arizona. From these folds,

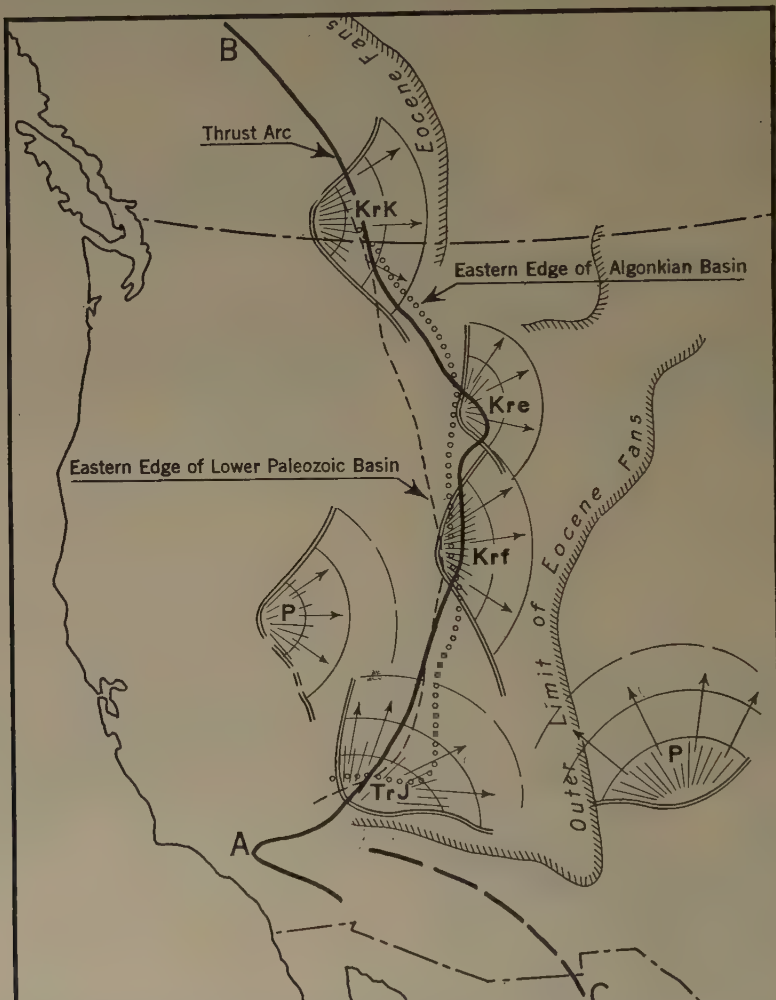

FIG. 4.—RELATION OF POST-MISSISSIPPIAN SEDIMENTATION TO BACKBONE OF THRUST BELT.

P. Sources of Pennsylvanian fans.
TrJ. Sources of Triassic, Jurassic fans.
KrK. Sources of Cretaceous Kootenai fans.
Krf. Sources of Cretaceous Frontier fans.
Kre. Sources of Cretaceous Eagle fans.

which are of post-Cretaceous (Laramide) age (or earlier in Arizona), have been eroded the thick Mesozoic formations, leaving along the crests a thin skin of lower Paleozoic beds covering the pre-Cambrian complex.

Fig. 5 shows the position of these folds and their relation to the principal known members of the thrust belt and the Eocene deposition.

The folded ranges were well established prior to the deposition of the principal Tertiary formations. The Uinta and Wind River mountains, for example, served to separate the Uinta, Green River, and Wind River basins, in each of which contemporaneous but disconnected deposits accumulated throughout Eocene time.

The thrusting reached its culmination, along the backbone, after the Laramide folding, and where it traverses the anticlinal axes it makes geologic intersections or "crossroads" of great complexity and interest. The principal intersections are the Little Belt in Montana, the Uinta and Torrey in Utah, the central Continental Divide area in Colorado at the east end of the Uinta axis, and the group in southeastern Arizona.

Montana Intersections

In Montana the main thrust backbone is represented by the crustal block between the Lewis-Big Belt thrust on the east and the Flathead-Bitter Root valley line of faults on the west. As it crosses the state from north to south, this backbone widens, showing a multitude of thrust strands and granitic intrusions. This complex phase coincides with the westward projection of the Big Snowy-Little Belt anticlinal axis. The following features are conspicuous in this area:

1. Long, narrow, close folds crowded around the western end of the Little Belt axis. These represent the accordionlike compression of this structure by the eastward Tertiary thrust.

2. Several nearly parallel thrust faults, which have a convex arc toward the east in this area, with a reentrant to the south followed by another forward curve in Yellowstone Park. While the major thrust is easterly, there are in rearward zones lesser thrusts of opposite throw. These may represent underthrusts.

3. Granitic intrusions. Many of the lesser ones, such as the Philipsburg batholith, the Anaconda and Powell range batholiths, and the White Sulphur Springs stock, are intruded along the thrust zones, which they partially obliterate. Each thrust strand of the entire system becomes clogged and obscured with granite where it crosses the area into which the Little Belt axis projects.

4. Mining districts. As the granites are distributed at specialized places in the crossroads area, so are the mining districts. Minor stocks along the eastern thrust line have the small Neihart and White Sulphur Springs districts in the Little Belt Mountains. The Boulder batholith, with its associated outliers, has a score or more districts, of which Butte, associated with a unique quartz porphyry phase, overshadows all the rest.[3] The stocks associated with the Philipsburg thrust have George-

[3] P. Billingsley and J. A. Grimes: Ore Deposits of the Boulder Batholith of Montana. *Trans.* A. I. M. E. (1918) **58**, 284–361.

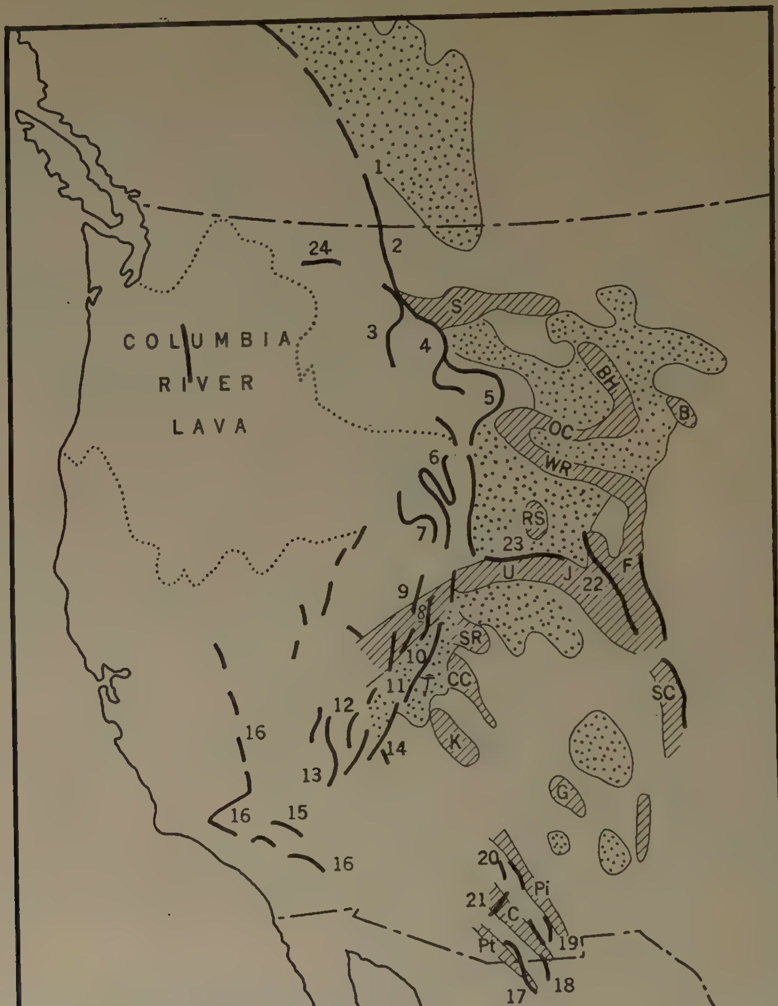

FIG. 5.—TECTONIC FEATURES OF THE ROCKY MOUNTAIN REGION.

LARAMIDE FOLDS—FIRST PHASE OF ROCKY MOUNTAIN SYSTEM (CROSSHATCHED)

S. Little Belt and Snowy Mts.
BH. Big Horn Mts.
B. Black Hills
OC. Owl Creek Mts.
WR. Wind River Mts.
RS. Rock Springs dome
U. Uinta Mts.
F. Front Range
J. Axial Basin
SC. Sangre de Cristo Range
SR. San Rafael dome
CC. Circle Cliffs dome
T. Torrey axis
K. Kaibab dome
G. Gallup anticline
Pi. Pinaleno anticline
C. Catalina anticline
Pt. Patagonia anticline

TERTIARY THRUSTS—SECOND PHASE OF ROCKY MOUNTAIN SYSTEM (HEAVY LINE)

1. Alberta overthrust zone
2. Lewis and Clark overthrust
3. Philipsburg overthrust
4. Little Belt-Bridger thrust
5. Absaroka overthrust
6. Bannock overthrust
7. Willard thrust
8. Cottonwood thrusts
9. Stansbury Mt. thrust
10. San Pete Valley thrust
11. Cedar City thrusts
12. Mormon Mt. thrusts
13. Goodsprings thrusts
14. Virgin Mt. thrusts
15. Calico Mt. thrust
16. Thrust line, eastern edge of Sierras
17. Patagonia thrusts
18. Gold Hill thrust
19. Gleeson thrusts
20. Mescal Mt. thrusts
21. Catalina Mt. thrusts
22. Leadville thrusts
23. North Uinta thrusts
24. Osburn fault

AREAS OF CONTINENTAL TERTIARY DEPOSITS (STIPPLED)

town, Philipsburg, Garnet, etc. In short, the mining districts in Montana that do not fall within this area are negligible. Of those that do, several, including Philipsburg, Marysville, Helena, Comet-Wickes and Hecla, are of the second order ($100,000,000), while Butte, with $2,000,000,000, is one of the major copper districts of the world. The Montana geologic "crossroads" has produced about $3,500,000,000.

Utah Intersections

The complex thrust belt, with its rearward normal faults breaking down into the Great Basin, crosses Utah from northeast to southwest. Eastward lie the flat-bedded plateaus: Green River in Wyoming, Uinta in eastern Utah, and Colorado on the southern line of Utah.

The Uinta anticline makes the Salt Lake valley intersection with its group of volcanic flows, intrusions and ore deposits. Farther south the San Rafael and Torrey anticlines converge to make the Marysvale intersection, with the same set of significant features. In the Salt Lake valley area[4] the following features are noteworthy:

1. The "accordion" folds developed across the Uinta axis by the Tertiary push from the west. These are well developed in the Oquirrh and Tintic mountains.

2. Thrust faults. A wide belt comes down from Wyoming and northeastern Utah, with the Absaroka, Bannock and Willard thrusts as the chief members. These are deflected and spread by the Uinta axis, with its high core of massive pre-Cambrian. Various strands are found in the intersection area, one main zone extending through Park City and the Cottonwoods, Spanish Fork, and Mount Nebo. Other important thrusts occur to the westward, in the Tintic, Oquirrh and Stansbury mountains. The occasional east-dipping strands may be underthrusts, as described in the Montana area.

3. Granitic intrusions. These are found in three main groups; one in the Park City-Cottonwood area, one at Bingham and one at Tintic. In Park City the diorite porphyry stock obliterates the south end of the Frog Valley thrust, and at Alta the granodiorite stock is similarly situated in respect to the Cottonwood thrust. The Tintic stock lies on the southern extension of the compressed and overturned limb of the Tintic folds. The function of thrust zones as guides for the injection of granites is clear.

4. Mining districts. Park City, Alta (Cottonwood), Bingham, Stockton, Ophir, Mercur and Tintic all lie within the Salt Lake intersection area. These have produced nearly $1,300,000,000; over 90 per cent of the metal output of Utah. The remaining 10 per cent has come principally from the southwestern Utah intersection, where the Torrey anticlinal axis is cut by the thrust belt near the Marysvale, Milford and

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[4] See also B. S. Butler: U. S. Geol. Survey *Prof. Paper* 111 (1920).
J. J. Beeson: *Trans.* A. I. M. E. (1927) **75**, 757–792.

Frisco mining districts. Cross folds, thrusts, intrusions and mining districts are here again characteristically associated.

Colorado Intersection

The Uinta anticlinal axis passing southeasterly through Axial Basin, then, with a sharp turn southward, into the White River Plateau, is intersected in central Colorado by the north-south belt of Rocky Mountain uplifts, 60 to 90 miles in width. The edges of this belt are steep faults which in many cases pass into overthrusts. The Williams and Mosquito faults on the west override toward the west, while the main Front Range fault shows overturn toward the east. It is probable that the general direction of the push was eastward, but that, as the Uinta Mountain and Colorado plateau tectonic blocks pushed against the Front Range uplift, they thrust *under* the western edge of the uplifted block, at the same time transmitting the eastward thrust to the eastern edge.

The Front Range uplift existed throughout Paleozoic time, although overlapped by upper Cretaceous formations. The Laramide folding rejuvenated it, so that the stages of final compression found here a light and high earth block. Such a condition accords with the underthrusting hypothesis.

The following features dominate this central Colorado area:

1. As it approaches the belt of uplift, the Uinta axis spreads and subdivides into three minor axes, which impinge against the western thrusts of the uplift near Radium, Leadville and Aspen.

2. The chief western thrusts are the Williams-Breckenridge and Mosquito-London zones. They are associated with crumples and involutions, overturned toward the west. The main zone of involutions traverses the principal axis near Leadville; a parallel zone 15 miles east passes through Breckenridge; a third, 35 miles to the west, crosses a southern subaxis of the Uinta system between Aspen and Crested Butte.

3. Granitic intrusions are grouped at these thrust-anticline intersections. There is also a belt[5] of minor Tertiary intrusions running northeasterly from Breckenridge across the Front Range uplift to Boulder. In Clear Creek and Gilpin counties this belt is marked by northeast folds, with a thrust along its southern margin. It connects, in a general way, the White River Plateau axis west of the uplift with the South Platte axis east of the Front Range. It may, therefore, be the deeply eroded roots of that part of an original White River-South Platte axis involved in the Front Range uplift between Leadville and Boulder.

4. The mining districts lie either in the western thrust involution belts—like Aspen, Red Cliff, Climax, Leadville, and Breckenridge—or in the northeast belt of intrusions across the uplift—like Silver Plume,

[5] E. S. Bastin and J. M. Hill: Geology of Clear Creek and Gilpin Counties, Colorado. U. S. Geol. Survey *Prof. Paper* 94 (1917).

Georgetown, Idaho Springs, Central City, Cariboo-Nederland and Gold Hill. The former group has mainly lead-zinc ores; the latter, silver-gold and tungsten. Climax, in the Archean rocks east of the Leadville thrust zone, has molybdenum. The districts of the two groups have produced $900,000,000 out of the Colorado total of $1,500,000,000.

Arizona Intersections

The important elements are northwest folds, thrusts of northwest strike and northeast movement, and northwest normal faults. Whereas in Montana and Utah the early folds are east-west, and the thrusts and faults either northwesterly or north-south, making obtuse intersections, here all are northwesterly, and the intersections are acute. Topographically, the late normal faults are as dominant here as are the Mission Range and Wasatch faults in Montana and Utah. The general pattern is as follows:

1. The master fold is the Galiuro syncline which extends from the corner of the state northwesterly to Miami, where it spoons up against the Colorado plateau. East of this syncline are the Pinaleno-Burro Mountain high areas, and west of it the Catalina high area and the Benson anticlinal axis. Farther southwest are the Sonoita syncline and the Patagonia-Cananea anticlinal axis.

2. Thrust faults are common in all the areas where the lower Paleozoic beds are exposed around the rims of the synclines and in the neighboring anticlines. They show a push toward the northeast. On the east flank of the Galiuro syncline are numerous strike faults which repeat the formation.

3. Granitic intrusions abound in the high areas, and can in many cases be closely correlated with the thrust planes in time and place. There is a nearly invariable sequence, in the Arizona Tertiary intrusives, of monzonite, quartz porphyry, and alaskite or pegmatite. Silica and sulfide mineralization—first pyrite, subsequently copper sulfides, zinc and lead—follow after the most acidic intrusive phase. The later phases and the mineralization are canalized in special portions or extensions of the main mass; either on one lobe, as at Miami; along one edge, as in the Patagonia Mountains; or in outlying fingertip stocks as at Cananea.

4. Mining districts, as in Montana and Utah, follow the granite in distribution, and are, therefore, largely on anticline-thrust intersections. On the Pinaleno axis are Hilltop, Dos Cabesas and Globe. Around the northern spoon of the Galiuro syncline, in or close to the basal sedimentary formations, are Miami, Superior, Ray and Christmas; on the Benson axis are Old Hat, Dragoon Mountains and Courtland-Gleeson; on Mule Mountains, Tombstone and Bisbee; and on the Patagonia axis, Helvetia, Harshaw, Washington-Duquesne and Cananea.

Morenci lies in a "window" where faulted lower Paleozoic formations, resting on a pre-Cambrian floor, are exposed beneath Tertiary volcanics.

The New Mexico group of districts, Silver City, Hanover and Santa Rita, lie in folded and faulted Paleozoics on the northeastern flank of the Burro Mountain high area.

Jerome (with a production of $400,000,000), Ajo (with $200,000,000), and Oatman (with $15,000,000) are important districts with no proved relation to intersections. The other districts within the area have yielded over $1,500,000,000.

Theory of Position

From the evidence of these crossroad areas in Montana, Utah, Colorado and Arizona, the following *theory of the position of mining districts* takes form.

1. The Tertiary thrust belt is characterized by the movement, measurable in tens of miles, of a shallow crustal layer toward the east. The layer has moved from the deep Paleozoic basin toward and on to the Continental shelf. In so moving, the layer has developed a zone of close folds and thrust planes, mainly overturned and overriding toward the east but with back strands that show a reversed movement that may be due to underthrusting.

2. The beds of the old (Paleozoic) Continental shelf east of the thrust belt are for the most part flat, and the thin Paleozoic formations are deeply buried beneath thick Mesozoic and Tertiary Continental deposits. Along certain anticlinal axes, however, erosion has exposed Paleozoic and pre-Cambrian at the surface.

3. Where the thrust belt encounters these axes, its folds and thrusts involve these lower formations, with the result that despite the relative shallowness of the thrust structures they penetrate deeply into and even through the stratigraphic column. Thus, whereas normally the thrust movement may slide out upon the Mesozoic or Tertiary rock with no real deformation of the crust proper, at these anticlinal intersections the thrust crumples effect a penetration largely within the crust itself.

4. Under these conditions channels are opened whereby material from within the crust, hot and under high pressure, can become fluid and escape to the cool, low-pressure surface. Hence we find the phenomena of vulcanism, intrusion and mineralization which are so closely knit together in time and place within the limits of the intersections or geologic crossroads.

This theory is compatible with the close relation of ore districts to the periphery of the Colorado plateau as noted by Butler; for, the parts of the periphery bearing ore districts coincide with thrust-uplift intersections of the kind described.

Distribution of Silver in Base-metal Ores*

By Samuel G. Lasky,† Member A.I.M.E.

(New York Meeting, February, 1935)

The writer has been interested in determining the mineralogic distribution of silver in the base-metal ore of the Ground Hog mine of the Asarco Mining Co. in the Central mining district of New Mexico.[1] This ore consists of a varitextured mixture of sphalerite, chalcopyrite, galena and pyrite in a quartz gangue. The average ore contains 14 per cent of zinc, 9.5 per cent of lead, 5 per cent of copper, and 10 oz. of silver per ton. Generally it is accepted that the silver in ores of this type, in which no definite silver minerals can be recognized, is contained in the base-metal minerals. Published assays of pure mineral specimens from many districts show that each of the base-metal minerals contributes in some degree to the total silver content of the ores, and to determine the proportionate amount contributed by each mineral in any specific ore it has been the practice to assay selected specimens of each mineral, the purity of which has been determined microscopically. There being no such assays available for the Ground Hog ore, and it being impracticable to have enough of them made to give average results, the writer resorted to a mathematical attack upon composite assays of large quantities of ore and concentrates. Surprising results were obtained, and it is the threefold purpose of this paper to present these results, to describe the mathematical method used, and to point out the value of using this method even when assays of pure specimens are available.

Value of the Mathematical Method

The obvious way of attacking the problem would be to separate *cleanly* large quantities of ore into its component minerals and then to determine the average silver content of each mineral by assay of representative samples. Since an absolutely clean separation is not feasible, it has been the practice, as mentioned above, to assay pure specimens of the different minerals. No one will contend seriously that the silver content of a base-metal mineral is constant throughout any particular deposit, and it will

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[1] S. G. Lasky: Geology and Ore Deposits of the Bayard Area of the Central Mining District, New Mexico: U.S. Geol. Survey *Bull.* in preparation.

be agreed that the assay of a single specimen therefore shows only the amount of silver in that particular specimen. Such an assay has not even the virtue of permitting an approximation of the information desired, for a small variation from the average silver content may give an entirely wrong picture of the silver distribution in the ore as a whole. As an example of this, let us assume a mixed-sulfide ore, containing 5 per cent of lead, 2 per cent of copper and 20 per cent of zinc, to which the galena contributes 0.7 oz. of silver for each per cent of lead (60.6 oz. per ton of galena), the chalcopyrite 0.3 oz. of silver for each per cent of copper (10.4 oz. per ton of chalcopyrite), and the sphalerite 0.2 oz. of silver for each per cent of zinc (13.4 oz. per ton of sphalerite), the total silver content being 8.1 oz. per ton. The galena therefore contributes 43 per cent of the total silver, the chalcopyrite 7 per cent, and the sphalerite 50 per cent. Assays of pure mineral specimens of this hypothetical ore may show 1 oz. of silver for each per cent of lead (86.6 oz. per ton of galena), 0.15 oz. for each per cent of copper (5.2 oz. per ton of chalcopyrite), and 0.13 oz. for each per cent of zinc (8.7 oz. per ton of sphalerite); the total silver content of the ore as indicated by these figures is 7.9 oz. per ton and is so close to the actual content that the specimen assays would be accepted as reliable, yet according to them the galena contributes 63 instead of 43 per cent of the silver, the chalcopyrite contributes 4 instead of 7 per cent, and the sphalerite contributes only 33 instead of 50 per cent.

If a number of specimens of each base-metal mineral in an ore were assayed, the average of the assays for each mineral would approach the true figure, and obviously if specimens were assayed for each ton of ore mined over an extended period and the averages used to compute the mineralogic distribution of the silver, the results obtained would be as accurate as one might desire. Such a task is clearly not practicable, but it ought to be possible to obtain results fully as accurate by a mathematical consideration of the assays of ore and concentrates produced over an equally extended period. These assays appear upon the desks of the mine and mill superintendents at regular intervals, and the task of computation calls for less time than that needed to pick a specimen and to examine it microscopically in order to be assured of its purity. The calculations involve only simple algebra, and a slide rule can be used for most problems.

Solution by Use of Concentrate Assays

The simplest example of the problem would be that of an ore containing only two minerals or of a more complex ore in which the silver content of all but two of the minerals is negligible. Under these conditions the following equation may be set up to show algebraically the silver distribution in the ore or concentrate, assuming the silver bearers to be galena and chalcopyrite:

$$\text{Pb}x + \text{Cu}y = \text{Ag} \qquad [1]$$

where Pb = assay percentage of lead,
Cu = assay percentage of copper,
Ag = ounces of silver per ton,
x = ounces of silver contributed by each per cent of lead,
y = ounces of silver contributed by each per cent of copper.

By inserting the assay values for two ore products, two equations are obtained that can be solved simultaneously. Or, if desired, the equations may be graphed and the values of x and y read from the intersection; if the assays used are from two such widely separated kinds of material as lead and copper concentrates, the curves will intersect at an angle large enough so that the intersection values will be reliable.

A consideration of assays of the zinc concentrate derived from Ground Hog ore and of the associated tailing, which contains most of the pyrite, indicates that the silver content of the sphalerite and pyrite in this ore is negligible, and that for purposes of calculation all silver may be assumed associated with the galena and chalcopyrite. By inserting in equation 1 assay values of lead and copper concentrates for a particular 9-month period, equations 2 and 3 respectively are formed. These concentrates represent 31,000 tons of ore containing 8.04 per cent of lead, 5.13 per cent of copper, 14.07 per cent of zinc, and 9.65 oz. of silver per ton.

$$37.0x + 12.2y = 41.2 \qquad [2]$$
$$7.6x + 24.3y = 12.9 \qquad [3]$$

Fig. 1 is the graphic solution of equations 2 and 3, from which it is seen that x equals 1.05 oz. of silver for each per cent of lead (90.9 oz. per ton of galena) and that y equals 0.20 oz. for each per cent of copper (6.9 oz. per ton of chalcopyrite). If it appears that the sphalerite is contributing an appreciable amount of silver, equation 1 may be amplified to read

$$\text{Pb}x + \text{Cu}y + \text{Zn}z = \text{Ag} \qquad [4]$$

and by using also the assays of the zinc concentrate, three equations can be obtained similar to equations 2 and 3 from which the three unknowns can be determined readily. For the Ground Hog concentrates these three equations for the same period covered by equations 2 and 3 are as follows:

$$\begin{aligned} 37.0x + 12.2y + 9.1z &= 41.2 \text{ (lead concentrate)} \\ 7.6x + 24.3y + 8.7z &= 12.9 \text{ (copper concentrate)} \\ 2.2x + 1.8y + 56.9z &= 3.9 \text{ (zinc concentrate)} \end{aligned} \qquad [5]$$

By solving these equations simultaneously the following results are obtained:

1.045 oz. of silver for each per cent of lead, or 90.4 oz. per ton of galena,
0.196 oz. of silver for each per cent of copper, or 6.8 oz. per ton of chalcopyrite,
0.022 oz. of silver for each per cent of zinc, or 1.5 oz. per ton of sphalerite.

The silver content of the pyrite then can be ascertained most readily by computing, from the values of x, y and z, the amount of silver in the tailing contributed by galena, chalcopyrite and sphalerite and ascribing the

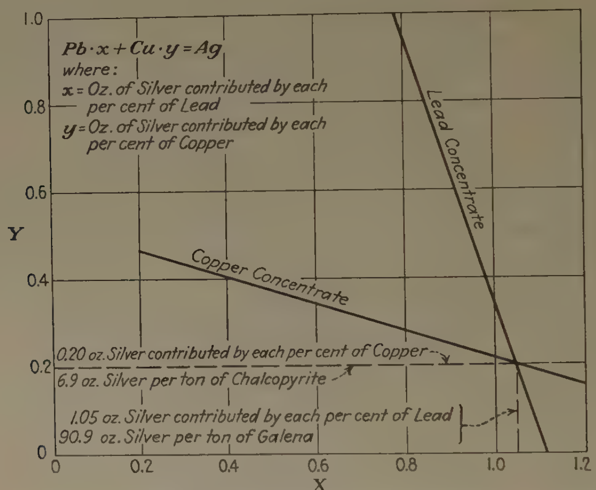

FIG. 1.—GRAPHIC SOLUTION OF EQUATIONS 2 AND 3, SHOWING AMOUNT OF SILVER CONTRIBUTED BY EACH PER CENT OF LEAD AND OF COPPER IN CONCENTRATES DERIVED FROM GROUND HOG ORE.

excess to pyrite. In this way it has been determined that the pyrite in the Ground Hog ore practically is barren of silver.

The silver content of the heads as computed from the ratios given above checks the assay of the heads by 0.06 oz. per ton. The same results could be obtained by setting up four equations in four unknowns, the equations representing the three concentrates and either the heads or tailing, but if this method is employed the silver must be equated against mineral instead of metal content, for the percentage of iron as given by assay includes the iron in the chalcopyrite and sphalerite as well as that in the pyrite. The equations would have the following form:

$$\text{Galena} \cdot x + \text{chalcopyrite} \cdot y + \text{sphalerite} \cdot z + \text{pyrite} \cdot v = \text{Ag} \qquad [6]$$

The silver must be equated against mineral content in any example in which the ore contains two or more minerals having the same metal component, and with this modification the method can be used with complex ores as well as with simple mineral mixtures such as the ore of the Ground Hog mine.

Solution by Use of Crude-ore Assays

Strictly speaking, the ratios given above indicate only the mineral association of silver in the concentrates. By inference, it would be assumed ordinarily that these ratios describe also the mineralogic distribution of silver in the crude ore, but this can and should be independently computed from periodic composite assays of the ore mined. Monthly composite assays are always at hand, and if such assays for half a year or more are used in the computations, the tonnage of ore represented is large enough to permit reliance upon the results obtained.

An equation similar to equation 4 or to equation 6 may be set up for each month, thus giving six or more equations in three or four unknowns. Whenever there are more independent equations than unknowns in a system, it is not possible to find values for the unknowns that will satisfy precisely all the equations, and the problem then becomes one of finding values that give the best solution for the system as a whole. This can be done by the method of least squares, in which each equation contributes to the solution. Several steps are involved but they are simple and one need know nothing about the theory behind the method.[2]

1. The unknowns in each equation must be written in the same order; i. e., x first, y second, etc.

Table 1.—*Monthly Composite Assays of Crude Ore from the Ground Hog Mine*

	Lead, Per Cent	Copper, Per Cent	Zinc, Per Cent	Silver, Oz. per Ton
June, 1932	9.49	5.48	12.39	9.77
July	10.45	5.39	13.08	10.75
August	7.47	5.19	13.77	8.53
September	7.47	5.70	12.76	10.25
October	8.13	5.36	16.80	10.17
November	9.65	4.80	13.42	9.99
December	8.53	4.93	13.09	9.82
Jan–Feb., 1933	8.58	4.56	14.67	9.63
Average	8.58	5.12	13.93	9.85

2. Multiply each equation by the coefficient of the first unknown in that equation and add the resulting equations. The sum is known as the First Normal Equation.

[2] See G. N. Bauer: Mathematics Preparatory to Statistics and Finance. New York, 1929. Macmillan.

3. Multiply each equation by the coefficient of the second unknown in that equation and add the resulting equations. This sum is known as the Second Normal Equation.

4. In like manner obtain a normal equation for each unknown.

5. Solve the normal equations simultaneously to obtain numerical values for the different unknowns.

Table 1 lists the monthly composite assays of the crude ore from which the concentrates represented by equations 5 were derived, plus 344 tons of direct-shipping galena ore, and the equations formed from these figures for the least square solution are as follows:

$$\begin{aligned}
9.49x + 5.48y + 12.39z &= 9.77 \\
10.45x + 5.39y + 13.08z &= 10.75 \\
7.47x + 5.19y + 13.77z &= 8.53 \\
7.47x + 5.70y + 12.76z &= 10.25 \\
8.13x + 5.36y + 16.80z &= 10.17 \\
9.65x + 4.80y + 13.42z &= 9.99 \\
8.53x + 4.93y + 13.09z &= 9.82 \\
8.58x + 4.56y + 14.67z &= 9.63
\end{aligned} \tag{7}$$

Each of these equations is multiplied by the coefficient of its first unknown, yielding equations 8, the sum of which is the first normal equation, 9. The second and third normal equations, 10 and 11, are found in a similar manner.

$$\begin{aligned}
90.1x + 52.0y + 117.7z &= 92.7 \\
109.2x + 56.3y + 136.7z &= 112.3 \\
55.8x + 38.8y + 102.9z &= 63.7 \\
55.8x + 42.6y + 95.3z &= 76.5 \\
66.1x + 43.6y + 136.6z &= 82.7 \\
93.1x + 46.3y + 129.6z &= 96.4 \\
72.8x + 42.1y + 111.7z &= 83.8 \\
73.6x + 39.1y + 125.9z &= 82.6
\end{aligned} \tag{8}$$

$$616.5x + 360.8y + 956.4z = 690.7 \quad [9] \text{ First normal equation}$$
$$360.8x + 215.2y + 568.3z = 409.0 \quad [10] \text{ Second normal equation}$$
$$956.4x + 568.3y + 1525.6z = 1084.6 \quad [11] \text{ Third normal equation}$$

By solving equations 9, 10 and 11, we find that in the crude ore there is:

0.396 oz. of silver for each per cent of lead, or 34.3 oz. per ton of galena,
0.902 oz. of silver for each per cent of copper, or 31.1 oz. per ton of chalcopyrite,
0.127 oz. of silver for each per cent of zinc, or 8.5 oz. per ton of sphalerite.

The accuracy of the least square solution is indicated by the fact that the silver content of the ore as computed from these ratios differs from the weighted average silver assay by only 0.05 oz. per ton.

These ratios should approximate closely those obtained from the concentrate assays and should differ from them only to the slight extent that the least square solution varies from a precise solution. But in reality the two sets of ratios differ considerably, and we are confronted with the anomaly that the galena in the crude ore is only slightly richer in silver than the chalcopyrite and only four times as rich as the sphalerite, whereas in concentrates derived from that ore the galena seems to be 13 times as rich as the chalcopyrite and 60 times as rich as the sphalerite. Furthermore, according to the crude-ore ratios, the galena contributes only 35 per cent of the silver, the chalcopyrite 47 per cent, and the sphalerite 18 per cent, whereas according to the concentrate ratios the galena should contribute 86 per cent, the chalcopyrite only 11 per cent, and the sphalerite only 3 per cent. Obviously, *the original premise that all the silver in this ore is contributed by the base-metal minerals is wrong*, and the crude ore must contain a silver mineral (or minerals) that is associated with chalcopyrite and sphalerite but that is floated with galena during concentration. As indicated by a microscopic examination of the ore, whatever silver minerals are present are submicroscopic in size, and they are evidently supergene minerals, for it is highly improbable that hypogene particles of such size can be liberated by crushing in an amount large enough to permit a notable change in the mineral association of the silver during concentration. The galena contains the usual minute dots of another mineral, which by analogy with the experimental results obtained by Nissen and Hoyt[3] is believed by some geologists to be a silver mineral, but these dots are much too small to be liberated in any appreciable amount even by the finest grinding used in milling operations. In the freshest Ground Hog ore mined to date, however, much of the chalcopyrite and sphalerite has a thin black chalcocitic tarnish or coating. This coating, and the sphalerite itself, would be ideal precipitants of supergene silver; the tarnished and coated surfaces would be ground together during the several stages of crushing and grinding of the ore preparatory to the flotation treatment, and the particles of supergene silver minerals in the coatings would tend to be rubbed loose. Once loose, they would come under the influence of the flotation reagents and would be driven into one of the base-metal concentrates, the particular concentrate being determined by the details of the flotation treatment.

If this explanation is valid, the implications are important. Obviously neither set of calculated ratios indicates by itself true conditions in *untarnished* ore. The silver-lead ratio calculated for the crude ore may be accepted for untarnished ore, however, because the supergene silver is associated with chalcopyrite and sphalerite; likewise the silver-copper and silver-zinc ratios as determined for the concentrates may be con-

[3] A. E. Nissen and S. L. Hoyt: On the Occurrence of Silver in Argentiferous Galena Ores. *Econ. Geol.* (1915) **10**, 172–179.

sidered only a little too high for the crude ore, because most of the supergene silver probably was freed from the associated chalcopyrite and sphalerite and driven into the galena concentrate. Therefore the following ratios may be accepted as indicating the average distribution of silver in untarnished, unenriched ore:

0.40 oz. for each per cent of lead,
0.196(−) oz. for each per cent of copper,
0.022(−) oz. for each per cent of zinc.

On the basis of these ratios the average primary ore is likely to contain only about 5 oz. of silver per ton instead of 10 oz. per ton as in the secondarily enriched ore currently mined, and the mineralogic distribution of the silver will be approximately as follows: 75 per cent in the galena, 20 per cent in the chalcopyrite, and 5 per cent in the sphalerite.

Conditions at the Ground Hog mine make it possible to check the validity of accepting the silver-lead ratio. The vein contains streaks of high-grade galena ore that is rich enough to be shipped directly to the smelter. The average metal content of several shipments of such ore, which totaled 344 tons and included lumps of galena picked from the sorting belt, was 57.0 per cent of lead, 3.64 per cent of copper, and 28.22 oz. of silver per ton; the zinc content was not determined. By ascribing 3.3 oz. of the silver to the chalcopyrite as indicated by the silver-copper ratio (3.64 × 0.902), and ascribing also a few tenths of an ounce to the little sphalerite that is present, it is calculated that the galena contains about 0.43 oz. of silver for each per cent of lead (37 oz. per ton of galena) as compared with 0.40 oz. for each per cent (34 oz. per ton of galena) as given by the least square solution.

Summary

The mineralogic distribution of silver in sulfide base-metal ores, and the average silver content of the different minerals, can be determined more satisfactorily by an algebraic consideration of assays of ore and concentrates than by the method commonly employed in which specimens of pure minerals are assayed. The latter method is reliable only if an impracticable number of specimens be assayed.

If the ore is unaltered, the figures calculated from the concentrate assays should check closely those obtained from a set of composite ore assays for the same period. If not, the ore must contain a silver mineral (or minerals) that is associated with specific minerals in the crude ore but that is carried into the concentrate of a different mineral; if the ore is strictly unaltered it must contain a primary silver mineral that has been overlooked; if it is partly altered and if the microscope discloses no primary silver minerals in particles large anough to be liberated by the usual degree of grinding, then the silver mineral is evidently supergene.

The quantitative determination of these features is not practicable in any other way.

At the Ground Hog mine, half of the average silver content of the ore mined during a particular 9-month period was contributed by submicroscopic supergene silver minerals two-thirds of which was associated with chalcopyrite and one-third with sphalerite, only a third of the total silver being contributed by galena; during concentration of the ore, however, the supergene silver minerals largely were driven into the lead concentrate, the practical result being that this concentrate contains over four-fifths of the silver in the mill heads.

Acknowledgments

The writer is indebted to the officials of the Ground Hog mine for placing their records of production at his disposal and for permission to publish the assay figures given herein. He wishes also to acknowledge his appreciation to those with whom he discussed the problem, particularly to Dr. Sterling B. Talmage, Professor of Geology, R. H. Reese, Professor of Mathematics, and A. S. Walter, Professor of Ore Dressing, at the New Mexico School of Mines, and S. Power Warren, Professor of Ore Dressing at the Colorado School of Mines. Messrs. H. G. Ferguson, C. P. Ross and C. S. Ross of the U. S. Geological Survey read the manuscript and offered welcome criticism.

DISCUSSION

(*John Wellington Finch presiding*)

S. G. Lasky.—I was rather fortunate in having a copy of Dr. Warren's discussion[4] mailed to me before the meeting, so that I am somewhat prepared. I think I should point out first that I tried to check this mathematical method mechanically. I tried to break some of the tarnish off in a small ball mill. Although I did get less silver in the cleaned stuff than in the original, I found that a lot of the galena and chalcopyrite were slimed and that the cleaned material had different base-metal ratios than the original, so that I would still have had to go back to a mathematical computation in order to find out anything. Therefore, I dropped any further mechanical testing.

Dr. Warren spoke of a stope in one mine where the ore was extremely high in silver without carrying any more than the usual amount of lead. I think that illustrates one of the advantages of using a mathematical method, because the miner and millman are interested in broad averages. The miner does not care what one particular stope will give him; he is more concerned with the average amount of silver in the ore as it goes to the mill, day in and day out, month in and month out, and in what percentage of the silver may be contributed by the galena, sphalerite and chalcopyrite.

Dr. Warren has quoted some assays on galena from the Ground Hog ore, and supplementing these assays he states that although the silver-base metal ratios may vary within broad limits at different mines in a district, at any one mine the ratios

[1] A large part of Dr. Warren's paper (p. 81, this volume) was originally submitted as a written discussion.

are remarkably constant. This statement is not convincing in the light of his assays. He has five assays that, as given in percentages, agree rather closely, but when computed in terms of ounces per ton they range from 6 oz. per ton of galena to 35. Incidentally, the high figure of 35 oz. per ton is pretty close to my computed figure of 34 oz. per ton.

This range from 6 to 35 oz. per ton stresses my contention that the assay of any particular specimen gives nothing more than the amount of silver in that specimen. If you assay two specimens you can get some sort of average, and if you assay a specimen for each ton of ore mined you would get an average whose accuracy nobody would deny. Theoretically, the results obtained mathematically are equivalent to this last average.

The mathematical set-up for this particular problem gives only the silver *controlled* by the different minerals and indicates nothing as to the nature of the association. According to Dr. Warren's figures, the sphalerite contains no silver. This result compares very well with my figure of 1.5 oz. per ton of sphalerite. Particularly since that 1.5 oz. represents a maximum, because it includes an unknown amount of supergene silver that might still be stuck to the sphalerite. The difference between a maximum of 1.5 oz. per ton of sphalerite and nothing per ton is nothing to quarrel about.

My contention that the silver must be supergene applies only to the Ground Hog ore, in which examination of polished specimens shows no hypogene silver minerals, even in microscopic particles. I do not believe that any hypogene particles of submicroscopic size could be knocked loose in any significant amount. We all are acquainted with the fact that it is not feasible to separate by grinding even such large particles as the chalcopyrite inclusions common in some sphalerite.

At the risk of being charged with having so much enthusiasm for the mathematical method that it beclouds my judgment, I might point out that the method can be extended to cover more complex mineral combinations, if sufficient analyses of the ore are given to show the entire metal content, including antimony and arsenic. We can compute from such analyses the mineralogic composition of the ore, and we can then set up mineral instead of metal equations. That is, we would have: galena times the ounces of silver contributed by each per cent of galena, plus chalcopyrite times the silver contributed by each per cent of chalcopyrite, and so forth, including in the equation tetrahedrite and any other silver minerals, and from these equations we could compute not only the silver contributed by the base-metal minerals but also that contributed by the silver minerals present.

L. C. Graton,* Cambridge, Mass.—Apart from the value that a method of this kind may have for shedding light on operating problems, especially with respect to the distribution of silver in the ore on the basis of averages, is it not a rather different matter to interpret two sets of computations that do not harmonize into a presumption of genetic significance?

The first question that arises is this: Is the particular interpretation adopted by the author the only way of rationalizing the two sets of figures? Are there not other guesses that might be tried that perhaps would be as good, as to assume that the silver occurs chiefly in some minor supergene coating? If there are other guesses that have not yet been investigated, the author's conclusion has the status of being only one of the guesses.

Another idea that comes to my mind is this: if it is possible to see supergene coatings, it ought to be possible, by existing technique, to determine whether those supergene coatings are unusually rich in silver; and it should be possible also to determine whether the minor ingredients of the different materials in the galena are silver

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minerals as well as to ascertain whether they are uniformly distributed through the volume of the galena grains, or whether they are distributed heterogeneously so that they may respond to the mechanical and physical and chemical processes of grinding and flotation differently, depending on whether they are distributed toward the centers of the grain or uniformly throughout the grains, or close to the margins, as sometimes may happen.

Finally, I should like to suggest that this seems to be a particularly good place for the application of spectrographic methods to minute samples that can now be taken from controlled spots on even a microscopically small grain and, so far as silver is concerned, very exact and reliable data can be secured as to the actual silver content, qualitative to be sure, or semiqualitative, from point to point within the grain.

Until there is more direct proof that the dark coatings contain the silver, it seems to me that such an idea is open to challenge. While it is an interesting suggestion, I should like more definite, more mineralogical, more chemical data in supporting that than just this means of rationalizing and harmonizing the two sets of conflicting mathematical figures.

H. V. Warren,* Vancouver, B. C.—This question has a practical significance sometimes. When most of the concentration was done by jigging, tabling and so forth, the tetrahedrite, which usually does contribute this silver in most of the instances that we know mineralogically, found itself with the galena. Then flotation of the galena was introduced, and while this often raised the lead concentrates to something like 95 or 97 per cent, their silver recovery fell sometimes to 67 per cent, showing that there was absolutely no tie, except that of chance, between the silver content of the ore and the galena. Tetrahedrite and galena had always acted alike on the tables. They do not in flotation. Silver content in base-metal ores is often due to a specific mineral, which has been occasionally identified definitely with chemical tests. There is not a shadow of a doubt on that point.

S. G. Lasky.—We are concerned, at least I was, with an ore that had no definite silver minerals that could be determined with the microscope. I prefaced my conclusion by saying that although the ore must contain particles of silver minerals, any interpretation beyond that depended on how large such particles must be before they can be liberated by the usual methods of grinding and crushing. My own opinion is that submicroscopic particles would not be liberated in amount sufficient to give a great change in silver-base metal ratios between the crude ore and the concentrate derived from it.

I tried to test the tarnish for silver chemically and found that I could not stop the action before the reagent started eating into the underlying mineral.

The galena does carry particles of the white mineral that, by analogy with experiments, is supposed by some mineralogists to be a silver mineral. Some time ago I took that question up with M. N. Short. He said that the particles were too small for him to determine whether or not they were silver minerals. But even if they are silver minerals, they are still much too small to be liberated.

B. M. O'Harra,† Joplin, Mo. (written discussion).—In Table 1 Dr. Lasky gives assays of several monthly composites of crude ore from the Ground Hog mine, and an arithmetical average for the entire period. On the next page he forms a series of eight equations from these assays, each containing three unknowns, and solves for the three unknowns by the method of least squares. The solution indicates the generalization that in the crude ore there is 0.396 oz. of silver for each per cent of

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* Lecturer in Mineralogy and Petrography, University of British Columbia.

† Eagle Picher Mining & Smelting Co.

lead; 0.902 oz. of silver for each per cent of copper; 0.127 oz. of silver for each per cent of zinc. Turning back to Table 1, if these factors are applied to the lead, copper and zinc assays of the various composites, the calculated silver content agrees very well with the average actual silver assay for the period as a whole, and for three of the individual monthly composites. For the other five monthly composites, however, the agreement is not at all good. Considering that there is not a great deal of variation in the composition of the various monthly composites from which his mathematical equations were formed, it seems to me that the author has generalized more than his data warrant and that his conclusions may be faulty for this reason.

S. G. Lasky (written discussion).—The averages given at the bottom of Table 1 are weighted averages, as stated in the last sentence on page 74, and not arithmetic, as Mr. O'Harra infers, although the two averages agree closely. Agreement between the calculated silver content and an arithmetic average would indicate only that there were no errors in the calculations, whereas agreement with a weighted average, which involves a factor—tonnage—not included in the calculations, emphasizes the reliability of the method used.

If my interpretation is correct that much of the silver in the Ground Hog ore is supergene, discrepancies are to be expected from month to month between the computed silver content and that shown by the monthly composite assays and the amount of discrepancy may be considered a measure of how greatly enrichment of a particular lot of ore differs from the average.

Distribution of Silver in Base-metal Ores

By Harry V. Warren,* Member A. I. M. E.

(New York Meeting, February, 1935)

During the past few years the author has had an opportunity to examine a number of base-metal mines in the western United States, France and Spain. Nearly all of these mines produced some silver, and laboratory studies of the relationship between the silver and the various base-metal minerals in the ore have given some interesting and, it is to be hoped, enlightening facts.

As this work was undertaken primarily to ascertain the amount of silver chemically associated with, not controlled by, the various base-metal minerals, the laborious and not always satisfactory method of picking out "pure" samples of each mineral from many localities was employed. However, the results obtained have justified the time that has been spent. Not only have the conclusions arrived at in different mining areas been in accordance with one another but in many instances they have afforded scientific support or explanations for much of the knowledge that operators in the various camps have acquired by practical experience.

Although many of the conclusions are not new, many of the facts are, and the results, if they do nothing else, serve to confirm the findings of some of the other workers in this field, particularly the work of Nissen and Hoyt[1] and of F. N. Guild[2].

Dr. S. G. Lasky[3] has suggested a novel method for determining from a series of algebraic equations the amount of silver controlled by each of the base-metal minerals but I doubt very much whether his method can be justified, chiefly because there appear to be more variables to be considered than the few that appear in his equations.

Typical Examples of Irregular Silver Distribution

Combination Mine, New Mexico, U.S.A.—In this mine an examination of the assay plans either of the mine or of the average mill feed or products

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[1] A. E. Nissen and S. L. Hoyt: Silver in Argentiferous Ores. *Econ. Geol.* (1915) **10**, 172.

[2] F. N. Guild: In summary form in Chapter 9 of Laboratory Investigation of Ores, Fairbanks. New York, 1928. McGraw-Hill Book Co.

[3] Page 69, this volume.

would suggest that the galena and chalcopyrite are responsible for all the silver in the ore and that no specific silver mineral is present. It is possible, however, to cite many examples that indicate the presence of some specific silver mineral. In one of the stopes of this mine, in December 1934, a fair tonnage of ore was mined assaying from 6 to 10 per cent lead, about 10 per cent zinc and about 9 per cent copper. This ore carried much more lead and copper than the average ore of the mine and yet was much lower in silver than the average. In another stope, ore that carried less than 1 per cent lead was low in copper and ran above 18 per cent zinc, and ran 50 per cent higher in silver than ore from the stope first mentioned, which, incidentally, carried only one ounce of silver per ton. Obviously we cannot hope to solve such distribution by mathematical calculations, however elaborate.

Centenillo, La Carolina, and Linares Districts, Spain.—At the various mines in these districts the mineralogy is extremely simple, as there is present only one base-metal mineral of any importance; namely, galena. The ore is relatively low in silver, a few ounces to the ton, and no silver mineral has, to the best of the author's knowledge, been recognized in any of these districts. The interesting feature here is the fact that the second-grade ore is invariably richer in silver than the first-grade ore.

A Simple Explanation for Irregular Silver Distribution

Many similar examples could be cited but the two given are typical. In both instances all could be easily explained by assuming the presence of minute quantities of one or more silver-rich minerals that although it, or they, might exhibit a distinct affinity for some particular base-metal mineral such as galena, could give evidence of their independent existence by turning up in unexpected places.

If this simple explanation is correct, we can determine whether or not the silver in the less complex ores is provided by the base-metal minerals, by diligently separating out the component base-metal minerals in an ore and determining their silver content, even if no specific silver mineral can be found.

Other workers frequently have found silver minerals in small quantities in camps where more than a few ounces of silver were carried in each ton of ore; therefore detailed examples in this paper will be confined to two mines carrying relatively small amounts of silver. Furthermore, although the ore in these two mines is of entirely different types, both mines belong to the same metallogenic province, so that the results are to some extent corroborative.

In the Silver City district, in March 1930, there were two producing silver mines, the Combination and the Ground Hog, both of which the author visited and, through the kindness of the mine officials, was able to collect representative samples. A preliminary minerographic exami-

nation of the two ores showing that the Combination ore would be the easier to separate cleanly, a careful selection was made from this mine of minerals relatively free from impurities.

Distribution of Silver in Minerals of Combination Mine, New Mexico

The three most important base-metal minerals in the Combination mine are sphalerite, galena and chalcopyrite, the first named being by far the most important. The minerals were selected after crushing, screening and classifying the ore and then hand-picking the product under the binoculars. A sample of this hand-picked product was retained

Table 1.—*Distribution of Minerals in Combination Mine*

	Composition, Per Cent						
	Ag	Zn	Pb	Cu	Fe	S	Total
Galena................*a*	0.025		85.53			13.00	98.53
Sphalerite.............*b*	tr	61.22			3.38	31.44	96.04
c	tr	55.62			3.82	29.92	89.38
d	nil	57.90			3.38	30.89	92.17
Chalcopyrite...........*e*	0.006			34.68	28.57	31.99	95.24
f	0.008			34.68	28.57	31.99	95.24
Mixed sulfides.........*g*	0.022	13.54	67.98	0.89	0.92	17.15	100.52
h	0.05						

a, good galena.
b, *c*, *d*, good sphalerite.
e, fair chalcopyrite.
f, chalcopyrite tarnished.
g, galena with a little sphalerite.
h, largely galena and sphalerite.

for polishing in dammar sections and the remainder analyzed, with the results listed in Table 1. From these assays it follows that:

1. Galena when uncontaminated carries probably not more than 0.025 per cent of silver.

2. Chalcopyrite when uncontaminated carries not more than 0.006 per cent of silver.

3. Sphalerite when uncontaminated carries little or no silver.

4. Galena and sphalerite when mixed carry an amount of silver that is roughly proportional to the amount of galena present.

5. The presence of only a small amount of extraneous mineral immediately causes a rise in the silver content of the mixture.

It might well be said at this juncture that the silver content in these minerals might change in different parts of the mine. This question can by no means be answered categorically; undoubtedly some changes do take place but, as will be shown in later analyses, there appear to be excellent reasons for supposing that the change is not great when any one mine is considered. Indeed, all the evidence at hand indicates that

although the silver content of the base-metal minerals, such as galena, varies within large limits at different mines, at any one mine the content is reasonably constant. In the Coeur d'Alene district, for example, three samples taken from different localities in the Bunker Hill and Sullivan mine showed by analyses a silver content varying by less than 0.0035 per cent[4].

Assuming that galena contains 85 per cent lead, it follows that 1 per cent of lead in galena will carry $\frac{0.025}{85} \times 291$ oz. of silver per ton; or, expressed in another way, 0.085 oz. of silver is contained in each 1 per cent or unit of lead. Similarly, assuming that chalcopyrite contains 34 per cent copper, it follows that 1 per cent of copper in chalcopyrite carries $\frac{0.006 \times 291}{34} = 0.051$ oz. of silver per ton. At the time the samples were taken the ore ran approximately as shown in Table 2.

TABLE 2.—*Analysis of Combination Ore*[a]

	Pb, Per Cent	Zn, Per Cent	Cu, Per Cent	Ag, Oz. per Ton
Ore milled	2.5	12.0	0.5	2.0
Mill heads	6.5	14.2	2.51	5.84
Lead concentrates	36.7	14.0	13.65	31.84
Zinc concentrates	1.7	52.9	1.18	2.36
Tailings	0.2	2.5	0.05	0.48

[a] U.S. Bur. Mines *Inf. Circ.* 6359.

Table 3 shows that the silver contributed by the galena, sphalerite and chalcopyrite in this ore is insufficient to account for the total silver

TABLE 3.—*Distribution of Silver in Galena and Chalcopyrite*

Silver Contributed by Galena, Oz. per Ton	Silver Contributed by Chalcopyrite, Oz. per Ton	Total Contributed by Galena and Chalcopyrite, Oz. per Ton	Total Actually Found, Oz. per Ton	Accounted for by Galena and Chalcopyrite, Per Cent
$2.5 \times 0.085 = 0.21$	$0.5 \times 0.051 = 0.03$	0.24	2.00	12
$6.5 \times 0.085 = 0.55$	$2.51 \times 0.051 = 0.13$	0.68	5.84	12
$36.7 \times 0.085 = 3.12$	$13.65 \times 0.051 = 0.70$	3.82	31.84	12
$1.7 \times 0.085 = 0.14$	$1.18 \times 0.051 = 0.06$	0.20	2.36	8
$0.2 \times 0.085 = 0.02$	$0.05 \times 0.051 = 0.00(+$	0.02	0.48	4

actually found in the ore. From these figures it seems clear that the silver is contained in minerals other than galena, chalcopyrite or sphalerite. Supergene enrichment was suspected and chalcopyrite, much tarnished,

[4] H. V. Warren: Silver-tetrahedrite Relationships, Coeur d'Alene District, Idaho. *Econ. Geol.* (1934) **29**, 693.

was analyzed, but it contained only 0.008 per cent silver, or but 25 per cent more than the purest material obtainable, and actually these results are hardly within the limits of analytical accuracy, owing to the small amount of material available.

Two or three minerals, present in minute quantities and as yet unidentified, are believed to be responsible for the silver present in this ore. No evidence was found to prove that supergene enrichment was responsible for any but a portion of the silver values occurring in the mine.

However, the results obtained at one mine might be the result of some error, so those obtained at another will be given in order to obtain more facts on which to base an opinion.

Distribution of Silver Values in the Ground Hog Mine

In this mine it proved to be impossible to get samples of uncontaminated sulfides but reasonably clean galena and sphalerite were picked out in the same manner as previously described, the various samples coming from different parts of the mine. The analyses are shown in Table 4.

Table 4.—*Silver Distribution in Ground Hog Mine*

	Composition, Per Cent							
	Zn	Pb	Ag	S	Fe	Cu	Insol.	Total
Galena		84.7	0.02	13.1				97.8
		83.3	0.08	12.8				96.2
		83.4	0.06	13.5				97.0
		83.5	0.06	13.2				96.8
		82.7	0.12	14.1				96.9
Sphalerite	64.1	tr	nil	32.3	2.4	nil	nil	98.8
	65.7	nil	nil	30.8	2.4	nil	nil	98.9
	63.7	tr	nil	32.9	2.2	nil	nil	98.8

It must, however, be stated that some of these determinations were made from samples weighing only from one to five grams. A silver determination frequently was run on a 400-mg. sample and amounts of silver below 0.01 might possibly escape notice.

Nevertheless, from these analyses it is probably fair to assume that:

1. Sphalerite does not carry silver in significant amounts.

2. Galena carries little silver and from a consideration of the analyses it seems clear that the less the contamination of the galena by other sulfides—indicated by the increase in sulfur content—the less the silver content of the galena.

3. It does not seem feasible to suggest that the silver is isomorphously replacing the lead, because the differences are not of the same order.

Furthermore it is unlikely that chance is responsible for the fact that the least contaminated materials in the Ground Hog and Combination mines give such close results as 0.02 and 0.025 per cent of silver, respectively.

However, even assuming that 0.06 per cent and not 0.02 per cent represents the average silver content of the galena, the percentage of silver carried by the galena is insufficient to account for the silver accredited to the galena as a result of the mathematical calculations of Lasky[5]. In reality 0.06 per cent of silver in galena is the equivalent approximately of 0.26 oz. of silver per unit of lead, while the amount mathematically calculated by Dr. Lasky is 0.40 oz. per unit of lead.

It might reasonably be asked whether the taking of a large number of samples of galena might not show a silver content nearer the highest figure of 0.12 per cent rather than 0.02 per cent. This question cannot be answered with complete assurance, but it can be said that the "cleaner looking" the galena the lower the assay, and the "cleanest" galena gave the 0.02 per cent result.

Results in Other Areas

To describe work done in other areas in the western United States is unnecessary. Some of this has been described in detail[6]. Nevertheless it is pertinent to review some of the conclusions arrived at in this work in so far as they are related to the problem under discussion. The chief conclusions reached in the papers cited are as follows:

1. Sphalerite when uncontaminated has never been found to carry silver in appreciable amounts. Wherever sphalerite has shown an appreciable silver content a careful analysis has shown the presence of ample quantities of some silver mineral, usually freibergite (argentiferous tetrahedrite), to account for any silver present. Zinc concentrates often show abundant silver but this has been shown to be due to freibergite, a proportion of which is usually found with the sphalerite concentrate to the disadvantage of the mill operator.

2. Pyrite is unimportant as a silver carrier. Uncontaminated pyrite probably contains no silver.

3. Chalcopyrite has not yet been tested in a sufficient number of localities. Inconclusive evidence suggests that it is relatively unimpor-

[5] Page 76, this volume.

[6] H. V. Warren and R. W. Loofbourow: The Occurrence and Distribution of the Precious Metals in the Montana and Idaho Mines, Ruby, Arizona. *Econ. Geol.* (1932) 27; The Occurrence and Distribution of Silver in the Silver King Coalition Mines, Park City, Utah. *Econ. Geol.* (1932) 27.

H. V. Warren: Relation between Silver Content and Tetrahedrite in the Ores of the North Cananea Mining Co., Cananea, Sonora, Mexico. *Econ. Geol.* (1932) 27; also reference of footnote 4.

tant. Three analyses of tolerably pure material gave results as follows: 0.006, 0.008, 0.009 per cent of silver.

4. The silver content of chalcocite, believed to be hypogene, varies greatly, and stromeyerite (CuAgS) may be the silver carrier in some areas. Supposedly uncontaminated chalcocite has been found by the author to carry as much as 0.37 per cent silver but much greater percentages have been reported by others.

5. Galena is an important silver carrier but probably not as important as heretofore suspected. In all mines where the silver content of the ore has been above 0.30 oz. per per cent of lead other silver minerals have been proved to be present. Furthermore, it seems probable that more precise work will lower the figure of 0.30 at least a little.

The silver content of galena in any one mine is usually reasonably constant but the content varies widely in different mines.

Origin of Microscopic and Submicroscopic Silver Minerals

Dr. Lasky[7] also considers that silver values are often due to supergene enrichment. That supergene enrichment of silver deposits takes place is well known but enrichment of silver deposits by late hypogene deposition is also of common occurrence, and it is this late hypogene enrichment, which often is overlooked, that may be in a large measure responsible for the silver values in many of the base-metal ores.

In the Coeur d'Alene district the silver-lead deposits owe a part of their silver content to argentiferous tetrahedrite, which formerly was considered secondary and supergene. However, mining has continued to depth and the silver content of the various ores has remained remarkably constant, thereby indicating that the tetrahedrite is probably of hypogene origin.

What does seem to be suggested by the preceding data is that the silver is introduced or crystallized towards the latter part of the mineralization and that therefore it is naturally found in base-metal ores of second grade, as at Linares, Centenillo, and La Carolina; in complex mixed base-metal sulfides as at Silver City; or in fine-grained rather than coarse-grained galena, as in the Coeur d'Alene mines.

Admittedly the evidence is not conclusive but there is a definite suggestion that in many of the fissure veins in the western United States the silver is contributed by late hypogene minerals. The effect of mining these deposits to depth will be that in so far as some of the silver is contributed by galena silver values may be expected to decrease as the percentage of galena decreases with depth, but that in so far as some of the silver is contributed by such minerals as tetrahedrite, which has greater persistence with depth, the decrease in the silver content will not be proportional to the decrease in the percentage of galena.

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[7] Page 75, this volume.

Summary and Conclusions

Silver in base-metal ores usually is only in part controlled by base-metal minerals and the remainder is due to the presence in the ore of small amounts of silver minerals, which are distributed in widely differing manners both initially in the base-metal minerals and eventually in the concentrates.

In the Ground Hog ore it is possible that some of the silver that is due to microscopic and "submicroscopic" silver minerals is hypogene in origin. However, this belief can be upheld only by the fact that this ore resembles those from other areas where mining has persisted below the zone of secondary enrichment and where silver values have continued to be substantial and are contributed in part by minute quantities of minerals that are definitely hypogene.

It is worthy of note, however, that results arrived at by such widely different methods as those of Dr. Lasky[8] and the author should agree as to the order of importance of the amount of silver controlled by different minerals; namely, galena first, with chalcopyrite a poor second and pyrite last. However, in regard to zinc the author's experience has been that in the zinc concentrates the silver found there is usually due not so much to silver minerals controlled by sphalerite as to the peculiarities of flotation, which result in some freibergite or allied mineral finding its way unwanted, and often unrecognized, into the zinc concentrates.

Acknowledgments

The author acknowledges his indebtedness to the many persons who have made this paper possible, and particularly to the late Mr. F. W. Richard of the Ground Hog mine and Mr. Ira L. Wright of the Combination mine.

The analyses on the Combination ore were made by Rodger W. Loofbourow at the University of Utah, Salt Lake City, with the assistance of the Commonwealth Fund. Those of the Ground Hog ore were made in the metallurgical laboratories of the University of British Columbia.

The material for this work was collected while the author was at the Balch Graduate School of the Geological Sciences, California Institute of Technology, under the auspices of the Commonwealth Fund of New York.

The work embodied in this preliminary paper has been carried on in the Geological Laboratories of the University of British Columbia, Vancouver, B. C. The writer is also deeply indebted to Dr. S. J. Schofield, of the Geology Department of that University, for critical discussion of this paper, and to Mr. J. Cummings for checking over details in the proofs.

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[8] Page 76, this volume.

DISCUSSION

R. D. McLellan,* Maurer, N. J. (written discussion).—In the quantitative classification of igneous rocks, it has been found expedient to establish "norms" calculated in terms of ideal minerals which are provisionally assumed to compose the rock. The "mode" or actual mineral composition of the rock is controlled by factors too complicated to calculate at the present time. Eventually and ideally the "mode" and "norm" will approach identity.

The paper by Dr. Lasky (p. 69) may be described as a method for the calculation of a "norm" for the occurrence of silver in base-metal ores. Factors are still too complicated for the mine or mill operator to depend upon such calculations; nevertheless they will tend to bring to light facts that otherwise might be overlooked.

The paper by Dr. Warren deals with a study of the actual mode of occurrence of the silver contents by hand picking and analysis of the mineral ingredients.

During the past 10 years I have made numerous detailed microscopical studies of the gold and silver occurrence in the ores from a wide variety of mining districts. In many cases the silver was found to occur largely as silver-rich minerals (such as freibergite, polybasite, etc.) capable of identification under the microscope. These minerals were found typically in a matrix of quartz and frequently were associated with minute well formed crystals of pyrite and sometimes bismuthinite.

Where the silver content of the ore is not accounted for in the base-metal minerals, and no silver-rich minerals can be identified, it is possible that the occurrence is similar to the other but disseminated on a submicroscopic scale.

In my examination of base-metal ores I have been impressed by the following:

1. In a given ore deposit the gold and silver contents of each of the base-metal ore minerals at widely separated portions of the mine are remarkably constant, provided that the minerals compared belong to the same stage of mineralization.

2. Conversely, the gold and silver occurring in a base-metal ore mineral serves as a valuable aid in the determination of the paragenesis of the more complicated ore deposits in which more than one generation of pyrite, galena, etc., is present. The gold and silver contents in a recurring base-metal ore mineral should be listed as one of the most important criteria to be established in the determination of the paragenesis of the more complicated ore deposits.

3. Sphalerite approaching ZnS in composition is essentially silver-free.

4. Marmatite, ZnS.NFeS, may contain notable amounts of silver. When the quantity of dissolved FeS is sufficient to render the marmatite nearly or entirely opaque in thin sections, it usually contains dissolved chalcopyrite and other minerals in addition to the FeS.

5. Clean, pure pyrite is very low in silver. The silver and gold contents in apparently clean pyrite with small but notable amounts of arsenic (presumably as arsenopyrite) may be important.

6. Chalcopyrite usually contains small but important quantities of gold and silver.

7. Galena, in practically all deposits, is the chief silver-bearing base-metal ore mineral.

During the past few years, the laborious task of hand-picking enough particles of each ore mineral to enable a fire assay to be made has been to a considerable extent replaced by the use of the quartz spectrograph on relatively minute samples.

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* Research Department, American Smelting & Refining Co.

Veins and Faults in the Bralorne Mine

By Ira B. Joralemon,* Member A.I.M.E.

(New York Meeting, February, 1935)

Neighboring mines, like men who live in the same environment, often assume similar characteristics. In the Bridge River area of the Lillooet district in central British Columbia there is a remarkable exception to this rule. The Pioneer mine has a simple fissure over 3000 ft. long, with no faults of more than a few feet and with only minor variations in width; the Bralorne mine, 2½ miles away at the other end of the same intrusion, has developed one of the most intricate vein and fault systems in the West. Hinged faults displace the main vein for hundreds of feet, and sometimes become valuable veins themselves. The width of ore varies in a few yards from 2 to 60 ft. Changes in grade of ore are just as abrupt. The rocks that follow the veins or are cut by them often grade into one another or into the ore with no definite contacts. Although the complexity of the structure has left many problems unsolved, the development has indicated a fascinating geological pattern.

The Bralorne is in the eastern portion of the Coast Range, 55 miles by spectacular mountain road from the Pacific Great Eastern Railway station of Bridge River. The adit tunnel runs easterly from Cadwallader Creek, a tributary of Bridge River that flows into the Fraser River. Steep mountains rise from 3300 ft. elevation above sea level at the creek to peaks and ridges at 8000 to 9000 ft. altitude. The lower slopes are heavily wooded while above 5000 ft. bare rocks, glaciers and snowfields extend far above timber line. See Fig. 1.

Story of the Bralorne

The Lorne claim, staked in 1897, was one of the earliest lode locations in the Bridge River district. At that time it was 70 miles by steep and treacherous trail from the railway. For the next 15 years Arthur Noel, Will Haylmore and other local prospectors mined the small, irregular, oxidized quartz veins to a maximum depth of 200 ft., and treated the ore in arrastres and later a five-stamp mill. The total production to 1912 was only $55,000. Noel and associates later formed the Lorne Amalgamated Mines Co., which they worked in a desultory way until 1925. Increasing sulfide and arsenide content in the veins

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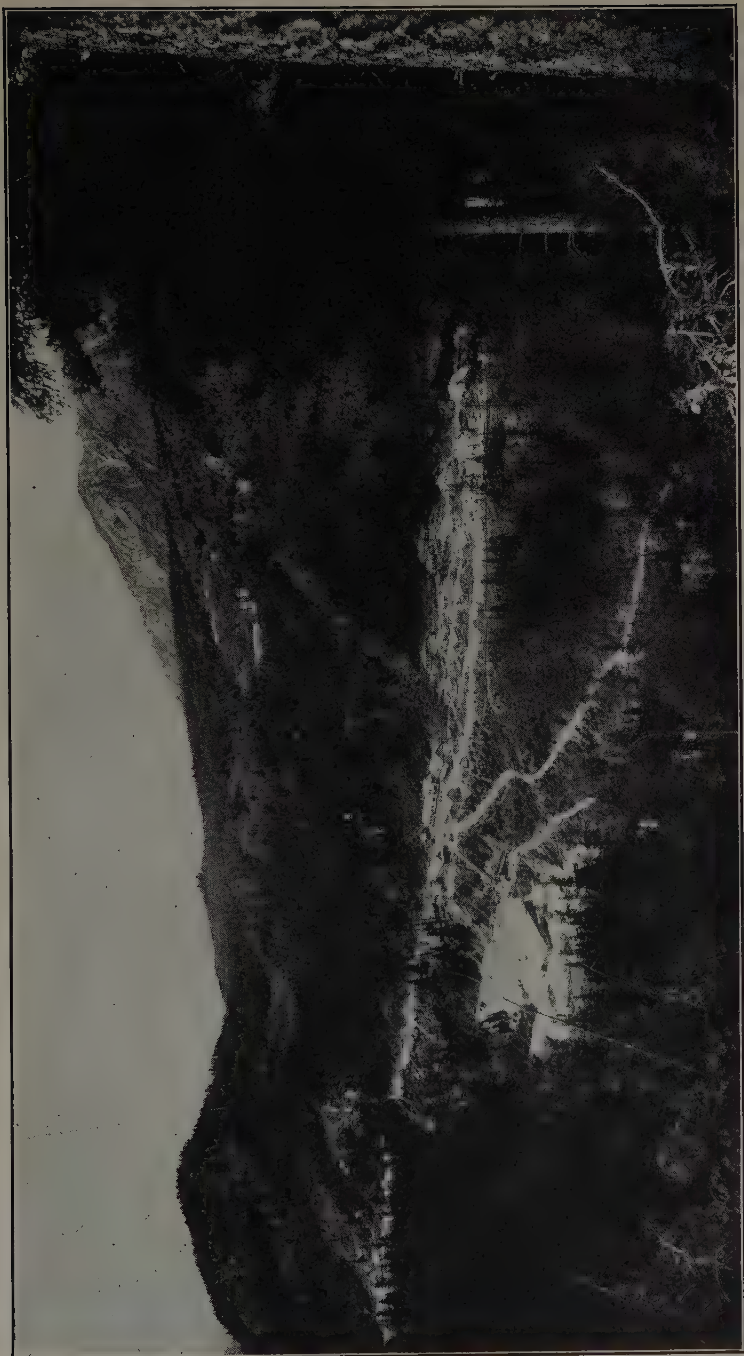

FIG. 1.—BRALORNE MINES, LIMITED.
Mill and eighth-level adit are at left of center. Old workings on outcrops are near the top of the ridge.

with depth had made the gold recovery by amalgamation too low to pay in so remote an area.

About 1925 Stobie, Furlong and Co., Canadian brokers, acquired the Lorne and a large group of adjacent claims for the Lorne Gold Mines, Ltd. Proceeds from the sale of stock were spent in driving a 3000-ft. adit tunnel 800 ft. vertically below the principal outcrops. In 1929 the tunnel was completed, and the principal veins were followed for many hundred feet. Only small orebodies were discovered. Heavily in debt, the mine was shut down and the price of the stock dropped to a few cents a share.

Two years later the Bralorne Mines Syndicate, headed by Austin C. Taylor, of Vancouver, paid off the indebtedness in return for an option on a 60 per cent interest in the property. After a little additional development, the Syndicate built a 100-ton flotation mill to treat the 21,500 tons of 0.7-oz. gold ore developed above the adit level, in the hope that the returns might be sufficient to finance further exploration that would find more important orebodies. A new company, called Bralorne Mines, Limited, replaced the old Lorne company. Results have more than justified the optimism with which $300,000 was spent before production started, early in 1932. The first year's profit returned the money advanced by the Syndicate. Without further investment of new capital the Bralorne has put in reserve nearly 300,000 tons of 0.35-oz. ore, enlarged the mill to capacity of more than 400 tons per day, and built an attractive, modern town. During the year 1934 earnings have averaged nearly $100,000 per month, and dividends declared will total $775,000. While the Bralorne has not quite caught up with its older neighbor, the Pioneer mine, it is already vying with it for the distinction of being the greatest gold mine in western Canada.

General Geology

The geology of the Bridge River area was first studied by Alan M. Bateman in 1912[1]. W. S. McCann published a more detailed report in 1922[2]. Ten years later W. E. Cockfield and J. F. Walker made a still more thorough study, particularly of the rock types[3]. The geology of the district as a whole has been briefly covered in articles on the Pioneer mine[4]. Matthew S. Hedley, geologist at the Bralorne mine,

[1] A. M. Bateman: Lillooet Map Area, B. C. Canadian Geol. Survey Summary Report for 1912, 177 ff.

[2] W. S. McCann: The Bridge River Area. Canadian Geol. Survey *Mem.* 130 (1922).

[3] W. E. Cockfield and J. F. Walker: Cadwallader Creek Gold Mining Area, Bridge River Dist., B. C. Canadian Geol. Survey Summary Report for 1932, AII, 57 ff.

[4] I. B. Joralemon: Pioneer Gold. *Eng. & Min. Jnl.* (1931) **132,** 483.

H. T. James: Features of Pioneer Geology. *The Miner* (Vancouver) (Aug., 1934) 342.

presented a paper at the Canadian Mining Institute meeting in Vancouver in November, 1934, on Structural Geology at the Bralorne. All of the subsequent observers have followed in general the classification of rocks and the outline of structure given by Bateman, though there are differences in detail.

The oldest rock in the vicinity of the Bralorne mine is the Bridge River series, considered by McCann to belong to the Cache Creek series of Pennsylvanian-Permian age. This rock consists of sheared and folded beds of chert, cherty quartzite, argillite and impure limestone, with occasional flows or sills of basalt and andesitic rock locally called greenstone. Rocks of this series have a steep dip, generally to the north or northeast. They outcrop on the mountainside several thousand feet east of the Bralorne mine.

Next in age comes the Upper Triassic Cadwallader series, made up of conglomerate, sandstone, argillite and impure limestone, with thick beds of the andesitic "greenstone" in the lower part of the formation. This greenstone is the most common wall rock in the Pioneer mine, and sometimes forms the vein walls in the Bralorne. The thickness of the Cadwallader series is many thousand feet. In the Bralorne mine it generally has a northwest strike and a nearly vertical dip. Because of the similarity of the interbedded greenstones in the Bridge River series and in the Cadwallader series, Dr. James considers the grouping of these rocks still uncertain.

The sediments have been invaded by several types of intrusive rocks, of which the oldest is a serpentine. Elongated masses of this rock sometimes follow the contact of sediments or greenstone with the later dioritic intrusions; sometimes follow the bedding of the sedimentary rocks of the Cadwallader series; and sometimes cut diagonally across the bedding. Serpentine seems to grade into greenstone and into the more basic variety of diorite. Because of this complex relationship, Cockfield and Walker consider the origin of the serpentine doubtful. While part of it seems clearly due to alteration of basic dikes, part may have resulted from the alteration of greenstone and diorite. This is one of the many questions in the Bridge River district that has not yet been solved. It is important because veins end when they come to the serpentine, and often contain spectacularly rich bunches of ore near it.

Following the serpentine came a series of dioritic intrusions allied with the Coast Range batholith of British Columbia. The oldest variety of diorite is a dark green, fine to coarse-grained rock classed by earlier writers as augite-diorite but reported by Cockfield and Walker to be more properly called hornblende-diorite. Several great lens-shaped bodies of this rock cut the earlier formations. The most important one, as far as now known, extends from the west end of the Pioneer mine 2½ miles northwest, to a point a few hundred feet west of the Bralorne.

Part of this body is shown on Fig. 2. The width varies from a few hundred feet to more than 2000 ft. While a thick mantle of soil and often of glacial drift makes it impossible to map accurately contacts on the surface, underground development in the Bralorne has shown that the diorite intrusion has a very steep dip.

Determination of the exact form of the augite-diorite is made uncertain by the gradual transition from diorite to greenstone. As contacts

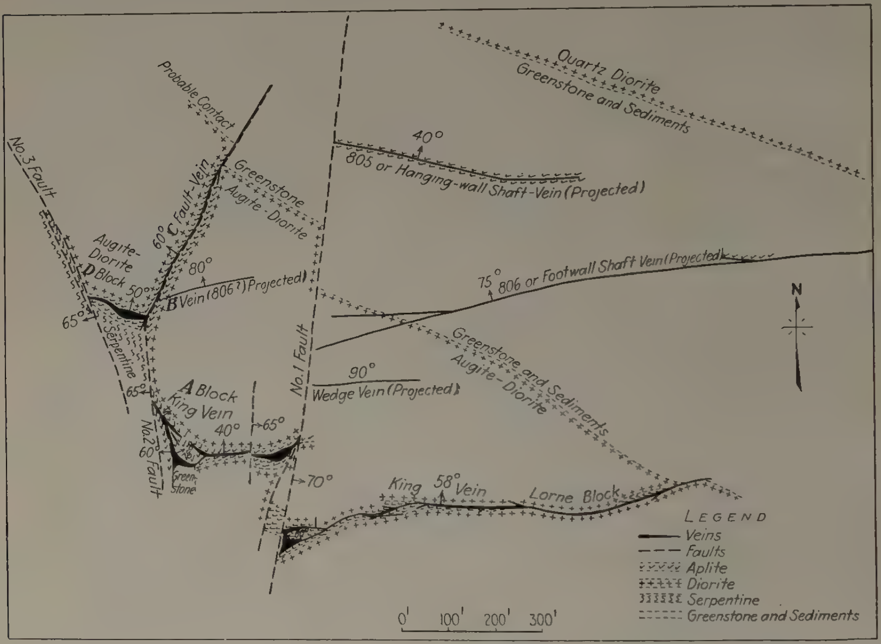

FIG. 2.—VEINS AND FAULTS ON SEVENTH LEVEL OF BRALORNE MINES.

are approached, the diorite becomes finer grained. Large inclusions appear of greenstone recrystallized to a fine-grained mass that differs only slightly from the finer grained varieties of diorite. The inclusions form an increasingly large part of the mass until only uncertain dikes of diorite can be distinguished. Finally the rock is clearly greenstone, but often so recrystallized that it can easily be confused with fine-grained diorite. The transition zone, in which it is a matter of personal preference whether to call the rock greenstone or diorite, may be many hundred feet wide.

An interesting example of this uncertainty is the wall rock in the greater part of the Pioneer mine. Bateman, McCann and the present writer called it augite-diorite, with greenstone inclusions, while Cockfield and Walker and James call it greenstone. Often no absolute distinction can be made.

The Pioneer vein extends from the east end of this large augite-diorite body into the adjoining greenstone, while the principal Bralorne vein runs diagonally across the west end of the augite-diorite into the sediments and greenstone on both sides of it. The relation is shown in the map, Fig. 2. Near the center of the same augite-diorite area irregular rich ore was mined near the surface in several veins that will soon be

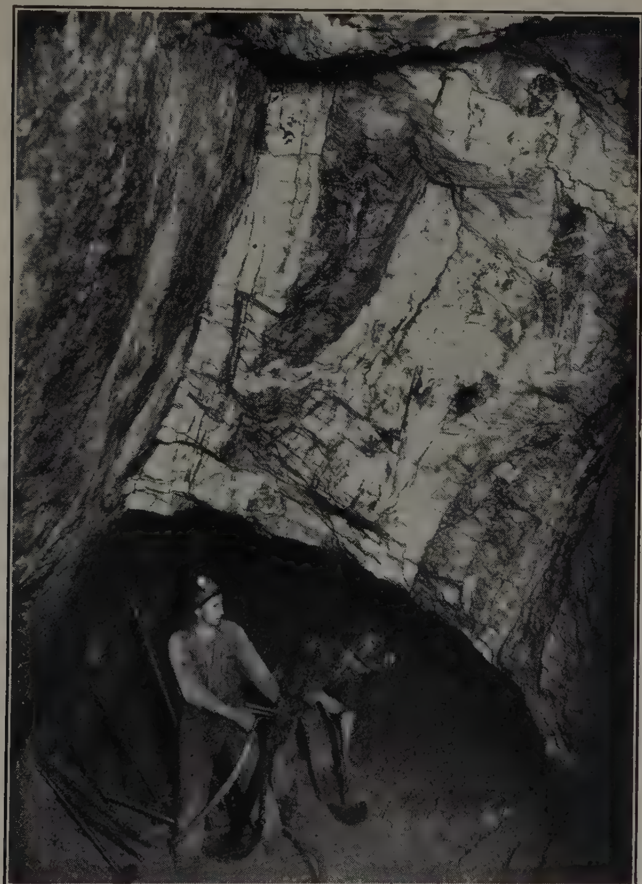

FIG. 3.—APLITE (DARK) AND QUARTZ (WHITE) IN KING VEIN, BRALORNE MINE.

prospected at depth by the Bradian Mines Limited, a subsidiary of Bralorne. Other gold prospects are in or near a second augite-diorite body that lies from 2 to 5 miles northwest of the one just described. Therefore the connection between this rock and the ore in the Bridge River district is close.

Later dioritic intrusions are much more acid, and may be grouped as quartz-diorite. They occur in many dikes of all sizes, cutting the augite-diorite and the greenstone and sediments. The most important known

body cuts diagonally across the course of the eastern part of the Pioneer vein, forming the wall rock of this vein for several hundred feet. Another wide dike lies northeast of the Bralorne mine, parallel with the augite-diorite and 800 ft. north of it. A smaller body occasionally forms the walls of the King vein in the Bralorne mine, grading to the aplite that will be described later on. Several thousand feet north of the Bralorne, high up on the mountain, there is a batholith of quartz-diorite that has been named the Bendor granite. While the relationship has not been proved, it probably belongs to the series of increasingly acid intrusions that followed the augite-diorite.

Last in the list of intrusive rocks comes a fine-grained buff or white dike rock that may be roughly classed as aplite. It is closely associated with the veins. Usually it followed the same fissures that later were reopened and filled with auriferous quartz. It often forms one or both walls of the Bralorne veins. This rock is practically always altered and pyritic underground, and iron stained on the surface. Under the microscope it is seen to consist largely of quartz and feldspar, frequently changed to sericite. Although Mr. McCann and others called this rock albitite, Dr. W. E. Cockfield found very little albite in a suite of specimens sent from the Bralorne, and considered the rock more properly an aplite[5]. Owing to the almost universal alteration along the veins, the aplite cannot be distinguished with any degree of certainty from altered diorite, greenstone or sediments. Three-fourths of the specimens sent Dr. Cockfield were reported to be so highly altered that their original character could not be told.

An additional uncertainty comes from the fact that the aplite or aplite-like alteration grades to ore. Nearly all of this material contains crisscross quartz stringers, disseminated pyrite and a little gold. Where the proportion of quartz increases only a little, the material becomes ore. Both along the veins and across them the mineralized aplite passes into the vein quartz and sulfides of the rich ore without definite contacts.

In the sketch presented with this paper all of the highly altered acid rock that accompanies the veins is mapped as aplite, though some of it without doubt was originally diorite, greenstone or sediments.

Quartz Veins

The Bralorne veins are made up of quartz with a very small percentage of other minerals. The quartz is sometimes in alternate dark and light bands, and sometimes in wide masses of pure white quartz containing no other visible minerals save gold. The banded quartz often, but not

[5] Letter to Bralorne Mines, Ltd.

always, is the richer. Early quartz in places is brecciated and cemented by later quartz. Usually from 1 to 3 per cent of the vein material consists of sulfides, chiefly pyrite and arsenopyrite, with small irregularly distributed crystals of sphalerite, galena, chalcopyrite and tetrahedrite. Calcite or brownish carbonates occur with the quartz. Now and then there is a considerable amount of sericite. In the ore, and more often in the lean silicified aplite of the footwall, mariposite or quartz stained green by mariposite are very common.

By far the greater part of the gold is in grains or crystals of the native metal large enough to be caught by jigs or blankets. About 75 per cent of the recovered gold is obtained by amalgamation of the products of these simple devices. The remainder of the gold is probably also in native form, but is so intimately associated with the sulfides that it goes into the flotation concentrate, which averages 4 oz. of gold and 14 per cent of arsenic. The silver content is negligible. The ratio of concentration is 30 or 40 to 1.

While the richer ore is associated most frequently with sphalerite and next with arsenopyrite, this is by no means a general rule. Beautifully crystalline coarse gold sometimes makes pure white quartz assay several dollars a pound. The common footwall rock made up of shattered aplite with crisscross quartz stringers and mariposite is occasionally ore of fair grade. Beautiful specimens have been found of crushed arsenopyrite cemented by crystalline gold. The association is so varied that the only generalization that can be made is that most of the gold came in a late phase of mineralization, after the earlier minerals had been deposited and fractured.

The quartz was fairly well oxidized to a depth of from 50 to 200 ft. The known oxidized ore was mined in the early days of the district. All ore on levels now open shows only a little iron staining on seams.

The veins occupy fault fissures on which there was motion both before and after the ore formation. In most places the later motion has resulted in strands of blue gouge on one or both walls or in streaks or films that give the quartz a banded appearance. Fault gouge often comes in at an acute angle from the wall and joins the vein fissure. In width the gouge varies from thin seams to bands 2 or 3 ft. thick. Post-ore strike faulting has sometimes drawn the ore out in long lenses, or has increased the thickness of quartz.

The grade of ore varies so greatly that the average mill head over a period of several months is the only figure that has any meaning. A drift or stope may assay 0.2 oz. for several weeks, and then a bunch of a few hundred pounds of spectacular high grade may raise the grade to 0.5 oz. or more. One drift 120 ft. long and 7 ft. wide averaged 5 oz. per ton. The average grade of the 170,000 tons of ore mined to date has been about 0.55 oz. gold per ton.

Vein and Fault System

The veins and faults in the Bralorne mine are so intimately associated that they cannot be described separately. The sketch map of the seventh level (Fig. 2) shows the pattern compressed into a small area. As the larger faults diverge in depth, the fault blocks are much longer on deeper levels.

The pattern consists of a series of nearly east-west veins with a northerly dip, cut by three branching cross faults that have shifted the western blocks to the north. East of the cross faults, the veins are narrow, fairly straight, and simple, with only minor branches that do not extend far into the walls. In the zone between the faults the quartz in the main or King vein is much wider. It sometimes splits into several strands separated by aplite so thoroughly mineralized that a width of 50 or 60 ft. is good ore. Cross strands parallel with the faults in strike but often opposing them in dip connect the branches of the King vein. The middle one of the three cross faults makes a slight turn to the northeast in the hanging wall of the King vein, and itself becomes a valuable vein. Whether the other two faults will anywhere be ore-bearing is not known, though often they do contain drag quartz.

King Vein

The King vein is by far the most thoroughly developed vein in the Bralorne. In the original Lorne block, east of No. 1 fault, this vein is comparatively straight and simple with a dip of 58° north. The width varies from a few inches to 8 ft. Many small branches leave the vein in foot and hanging wall. The widest and best ore is often near the branches, though these can seldom be followed for more than a few feet away from the main vein. A flat footwall branch that leaves the vein above the seventh level may possibly be a strand of the Woodchuck network of small veins, from which shallow ore was mined 400 ft. farther south. In the Lorne section the walls of the vein or of the aplite dike that accompanies it are augite-diorite. The vein pinches to a barren fissure in the sediments east of the diorite. It has not yet been followed to a second body of diorite farther east. There has been little change in the character of the vein with depth from the bottom of the oxidized zone, which here is 700 ft. on the dip above the seventh level, to the lowest, or eleventh level. Ore has been in irregular shoots with steep pitch. The tenth level was in a lean zone, with the eleventh level improving again. If the vein had continued as it is in this block, the Bralorne would have been a very small mine.

At the west end of the Lorne block the vein is complicated by a series of small north-south cross veins, dipping steeply west. On the

fourth level, here just below the surface, the King vein splits and is lost before it reaches the main north-south vein, called the Turnsheet. On the sixth level also the King and Turnsheet series of veins lose their identity in a network of lean and irregular north-south and east-west strands. On the seventh level the Turnsheet vein is cut off by the east-dipping No. 1 fault just at the point where the Turnsheet joins two branches of the King vein. The result has been an irregular delta-shaped body of rich ore with 50 ft. maximum width.

In the *A* block, between No. 1 and No. 2 faults, the King vein is very much wider than in the Lorne block, and is so different in character that it hardly seems like the same vein. The motion on No. 1 fault has tilted it upward to a 40° dip. The projected point of hinging is close to the surface, which here is below the fourth level. On the seventh level the horizontal displacement of the King vein to the north by this fault is 200 ft., while on the tenth level, 380 ft. vertically deeper, it is 280 ft. The vertical displacement is 100 ft. upward on the seventh and 150 ft. on the tenth level. As No. 1 fault dips east and No. 2 fault west, the two come together at the surface in a broad crushed zone seen in the old West tunnel. On the sixth level the two faults have split into many branches, with small twisted blocks of vein between them. On the seventh level for the first time there is a continuous vein in *A* block. As Fig. 2 shows, the vein is bent there in a bow concave to the north, as though the block had been subjected to end pressure that collapsed it. This bending of the vein in the *A* block has increased its length on the seventh level to 400 ft., while the distance between faults is only 270 ft. East and west of No. 1 fault the vein is sharply bent away from the direction of drag that would be expected. At the west end of the block the vein splits around an enlarged part of the aplite dike, and is bent sharply to the north until for 120 ft. it is parallel with No. 2 fault in strike but opposite in dip. The stretch of 5-oz. ore mentioned above is in this part of the vein. Just below the seventh level the quartz strands in the aplite are so close together that the whole mass, 60 ft. wide, is 0.5-oz. ore. Near No. 1 fault the width of quartz is more than 20 ft., and the stoping average for the whole block is about 12 feet.

On deeper levels the *A* block of the King vein is much longer, because of the spreading of the limiting faults. The bending of the vein is not quite as pronounced as on the seventh level. It forms a flattened S instead of a bow. On all levels the vein branches much more than in the Lorne block, and the average width is much greater.

The *D* block, at the west end of the developed area, is a wedge between the northeast No. 2 fault and the northwest No. 3 fault. The No. 2 fault apparently branches off from the No. 3 with a line of intersection that plunges down to the northwest. No. 2 fault has shoved the King vein to the north again and tilted it back to a dip of more than 50°.

The projected point of hinge is below the eleventh level a little north of the King vein.

In the *D* block the vein is wider than in the Lorne block, but not as wide as in the *A* block. On the eighth level it has its normal east-west strike, with little bending near the faults. On the seventh, and still more on the sixth, level the vein is bent around to the northwest, until on the sixth level it is practically parallel with No. 3 fault. The result of this twisting is that the length of the vein in the *D* block is about the same on all three developed levels, although the distance between faults decreases rapidly toward the surface.

No. 2 fault splits below the sixth level. The branches diverge in depth, with most of the motion on the flatter west branch. The *D* block has not yet been developed below the eighth level.

The structure in the *D* block is complicated by the fact that there the vein is very close to the west contact of augite-diorite with serpentine and greenstone. This contact strikes northwest, with a steep or vertical dip. It may have had something to do with the bending of the vein to the northwest.

The King vein has not yet been found west of No. 3 fault. Beyond this fault the rock thus far encountered has been serpentine or greenstone. A doubtful surface correlation suggests that the total displacement to the north on all three faults combined—which are together at the surface—is 1000 ft. If this is true, a 500-ft. crosscut will be required to find the vein beyond No. 3 fault. It seems likely that the vein will still have augite-diorite walls, as the nose of the long intrusion will be offset to the north with the vein.

C Vein

Wherever No. 2 fault is developed, it contains crushed quartz. At first it was assumed that this was only drag from the King and other veins. Further work proved that the post-ore motion on this fault followed an important west-dipping cross vein, like the Turnsheet vein, but much larger. The combined No. 2 fault and vein are called the C vein.

The ore found thus far in this vein is north of its intersection with the *D* block of the King vein. Here the fault vein turns to the northeast. It has been followed for several hundred feet on the sixth, seventh and eighth levels. Before it reaches the surface, here about 300 ft. above the sixth level, it must run into the broad fracture zone at the intersection of faults 1 and 2. On the tenth level the splitting of No. 2 fault makes it uncertain whether or not the C vein has been found. This vein consists of several feet of heavy blue gouge that contains fragments of crushed quartz, and often is fair ore. With the gouge are drawn-out lenses of auriferous quartz that reach a maximum width of 8 ft. Partly because

of the strike faulting, the grade of ore is exceedingly uneven. Areas that are lean on the level are rich a few feet above it. Occasional bunches of high-grade ore that assays several dollars a pound bring up the average. A length of several hundred feet can be stoped at an excellent profit.

To the northeast the C vein passes from augite-diorite into greenstone and sediments. It becomes smaller, though there is still fair ore. Within a few hundred feet the C vein will meet No. 1 fault at an acute angle. As that fault dips east while the C vein and fault dip west, it is quite uncertain what will occur at the intersection.

To the south, C vein mineralization continues along No. 2 fault between the blocks of the King vein, though it is generally lean. The cross structure has not yet been developed south of the *A* block of the King vein. There is some tendency for the quartz of the King vein to turn south along No. 2 fault, in addition to the bend to the north toward the *D* block.

Shaft Vein

The Shaft vein outcrops about 300 ft. north of the King vein. It is nearly parallel with that vein. On the surface it consists of iron-stained aplite several feet wide, with strands of oxidized quartz from which rich ore was mined many years ago. In the outcrop and all the developed part of the Shaft vein the walls are Cadwallader sediments northwest of the augite-diorite intrusion. In this area there is little greenstone. The sediments consist largely of partly silicified argillite, with some chert bands.

The shaly walls of the vein were blamed for the fact that until recently development was disappointing. In the old Wedge tunnel level, 200 ft. below the outcrop, the vein consists of several feet of very lean pyritic quartz, with an aplite dike in the hanging wall. On the eighth level, 700 ft. vertically deeper, a drift followed a small fissure that was thought to be the Shaft vein for 1200 ft., passing under the best outcrops. The strike is a little more north of east than that of the outcrop. The dip from surface to the eighth level was 75°. In the long drift the only ore was one little shoot of high grade 20 ft. long where a hanging-wall branch and an aplite dike left the vein.

In the past year an eighth-level crosscut found a new vein 500 ft. north of this supposed Shaft vein. The strike is east and west, practically parallel with that of the Shaft vein outcrop. The dip of 40° north projects up to the Shaft vein in the Wedge tunnel. Evidently the vein split about at this level. A small footwall fissure seen there may be the steep branch that was first developed on the eighth level.

The new hanging-wall or 805 Shaft vein is rapidly becoming valuable. It has been followed on the eighth level for more than 400 ft. east from

No. 1 fault. Three-fourths of this length is ore of average grade from 2 to 5 ft. wide. For the whole length the quartz is in the middle of an aplite dike 30 ft. wide. The vein is remarkably straight and uniform. As the distance up the dip to the Wedge tunnel level is 1200 ft., there are great possibilities above this level. The vein may continue many hundred feet farther east, as it is approaching the 806, or footwall Shaft, vein at a very acute angle.

It is not known what will happen to the Shaft vein west of No. 1 fault. The probable offset on this fault would throw it north practically to the intersection of No. 1 with the C vein, on which there will be an additional offset. If the C vein has the same effect on the Shaft vein as it did on the King vein, the ore may be much larger at this intersection.

One of the most important results of the Shaft vein development has been to prove that strong fissures and good ore occur outside of the augite-diorite, even where the walls are shaly sediments that ordinarily would be considered unfavorable.

Other Veins

Other veins in the Bralorne property have not yet proved important. The Wedge is a steep east-west vein between the Shaft and the King veins. It has thus far been very narrow. The Woodchuck veins are a network of small east-west veins with a north dip cut by north-east cross veins. Good ore was mined from close to the surface many years ago. As suggested above, the principal vein of this group may have joined the King vein near the seventh level.

Still further south are other east-west veins, with a steep dip. Very little work has been done on them, either on surface or underground. Where exposed they are small, but in places rich.

History of Vein Formation and Faulting

The eventful history indicated by the veins and faults is about as follows:

1. After the intrusion of all save the last phases of diorite, east-west and north-south fracturing of about the same age took place in the diorite and in the sediments and greenstone near it. The east-west fractures were by far the most frequent and the stronger. They cut the long axis of the large diorite intrusion at an angle of about 30°. The amount of faulting on these early fractures was small.

2. Acid dikes, usually of aplite but sometimes of quartz-diorite, were intruded along the stronger fractures, forming enlarged chimneys at the intersection of the two sets of fractures.

3. Both the east-west and the north-south fractures were reopened, either along the borders of the aplite dikes or through the center of them.

4. Mineralization with vein quartz and its associates took place along both sets of fissures. The earlier lean quartz partly replaced the aplite as well as filling the open spaces. This quartz was fractured, and later gold-bearing quartz refilled the fissures. The larger aplite chimneys at fracture intersections were sometimes so thoroughly refractured and mineralized that they form ore for a width of 50 or 60 feet.

5. After the close of mineralization, faulting took place on a much greater scale. Most of the motion was along the north-south fractures; both the earlier fractures that had been mineralized and new ones that were not open at the time of aplite intrusion and mineralization. There was comparatively small strike faulting along the east-west veins in this last period. The faulting apparently was a thrust upward from the southwest at an angle of about 30°. It moved the westerly blocks to the north and up, regardless of the dip of the faults, and tilted the different blocks at different angles so that the faults are hinged. The west component of the thrusting compressed the more westerly blocks, bent the veins in them, and sometimes twisted them in a direction opposite to the normal drag.

The events in this complicated history overlapped, so that there was continual fracturing during and between the periods of intrusion and mineralization.

Field evidence points to the conclusion that the veins are the last step in igneous activity that started with the augite-diorite; or perhaps even with peridotite, which was the ancestor of the serpentine. The intrusions from a common source became more acid, through quartz-diorite and aplite, until finally they graded into the more aqueous solutions that formed the veins.

DISCUSSION

(John Wellington Finch presiding)

H. V. Warren,* Vancouver, B. C.—A great deal of the material that is classed as mariposite is not that at all. We do not know what it is. I have had many samples submitted to me in the laboratories, which undoubtedly are not mariposite. While "mariposite" is frequently found with gold, unfortunately gold is not always found with "mariposite," as many people that have been buying stock in British Columbia have found out to their cost.

The second thing about the minerals accompanying gold is that although most of the gold, as the author says, is coarse free gold and the metallic minerals are very small in amount, nevertheless the metallic minerals are there, and certainly in the Pioneer mine an increase of sphalerite or arsenopyrite almost inevitably points to rich ore findings.

On the eastern margin of the coast range batholith, which runs in a northwest-southeast direction, parallel to the coast of British Columbia, there is a whole series

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of prospects, some of which look as though they might become profitable mines. In every case that we know of these mines are related, not to the main coast range batholith, but to small associated intrusives. Farther to the north exactly the same set of conditions crop up, although there are fewer prospects there at the present time.

J. A. Dresser,* Montreal, Que.—I should like to emphasize what Mr. Warren has said, that the distribution of mineral prospects in British Columbia is strikingly related to the inner border of the coast range batholith. As he has pointed out, it is a factor of much importance looking to the broad development of that country for the future. Long areas are very difficult of access, of course, but treated as a whole it is one of the great potential fields in the view of the mining geologist in British Columbia.

With regard to the matter of mariposite and gold, one is impressed by the frequent repetition of this association through northern Ontario and Quebec. I cannot say whether it is of great importance, but the association is noticeable. On one occasion, too, I found a body of rock in the Appalachians impregnated with a considerable amount of mariposite around an intrusion of a serpentine rock. I sampled a considerable area with more vigor and zeal than might be justified. It did not yield any mine, but it yielded upwards of one dollar of gold, on the average. The samples rewarded the curiosity but not the effort.

H. V. Warren.—Might I say also that on the western margin of this coast range batholith in British Columbia there is, likewise, a series of veins of which the mineralogy is entirely different, these veins often being of extremely high grade but very small. So, while the eastern margin of the batholith contains or carries our main hopes at the present time, there is a possibility that if we can curb our wild ideas of having enormous companies, and go in for small but profitable operations, small mines will be found along the western batholith. I am referring only to gold now.

P. Krieger,† New York, N. Y.—In connection with the so-called maraposite, is anything known as to the age of the mineral with respect to the gold in the veins, and whether or not there is also roscoelite, commonly associated with gold, particularly in the various regions mentioned?

H. V. Warren.—At the University of British Columbia we are now examining something like thirty of the mines that contain these gold veins. The question is therefore *sub judice* at present and I can only say that the so-called mariposite and gold are very closely related.

Mr. Mellor, in regard to his work in South Africa, said that gold is frequently accompanied by sericite, but also sericite is not always accompanied by gold. The same is true of the "mariposite." The association is very persistent, but while we get hundreds of prospects with it in British Columbia, many run only one or two dollars in gold. But this little gold has been the downfall of many companies because, unfortunately, "mariposite" does not necessarily mean that gold in economic amounts will be there in connection with it.

P. Krieger.—Do you know of any other districts where it appears?

H. V. Warren.—There are some, but even in those districts, although it is possible that ore will be found, I should say it is not always probable.

I. B. Joralemon (written discussion).—Answering Mr. Krieger's question, the field association suggests that the mariposite at the Bralorne is earlier than the gold.

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* Mining Geologist.

† Instructor, School of Mines, Columbia University.

Apparently barren quartz with mariposite and pyrite closely followed the aplite dikes. Later quartz with arsenopyrite, galena, sphalerite and a little tetrahedrite are much more closely associated with the gold.

In some of the California mines also the mariposite and a dense early quartz seem to antedate the gold and its associated minerals.

I hope some one will be able to explain the very common association of mariposite and of green staining that resembles mariposite with gold.

Chertification in the Tri-State (Oklahoma-Kansas-Missouri) Mining District

(New York Meeting, February, 1934)

PART I

By George M. Fowler* and Joseph P. Lyden,† Members A.I.M.E.

The fact that most of the zinc-lead ores of the Tri-State district are associated with abundant chert in the Boone formation has led us to give much consideration to the manner of occurrence of the chert throughout the formation and to its relationship to the structural and other geologic features having bearing upon the sulfide mineralization. Necessarily the question of the source and the manner of deposition of the chert has come up in the course of these studies. We do not pretend to have arrived at the answer to all the questions regarding the chert. However, we have made a very large number of field observations, which present certain facts about the chert in this district that may be worth elaboration. Whatever theories may be drawn upon to explain the presence and distribution of the chert must necessarily be capable of reconciliation to these facts. The more important theories that have been presented are briefly summarized, and some of them discussed, in this paper. This paper is in three distinct parts, each complete in itself, wherein is recorded the evidence gained from three separate methods of attack.

In an earlier paper,[3]‡ we briefly described the chert and its relationship to the ore deposits.

Chertification, as used in this paper, means the replacement of limestone by introduced silicic acid. It is a common phenomenon in many widely distributed limestones. The products of chertification may be chert, cotton rock, or tripoli, depending upon the extent to which the replacement has been carried. Chertification is used instead of silicification in order to reserve the latter for the siliceous emanations so common in connection with the sulfide ore deposits of this and many other districts. Broadly, it is meant to include all silicification in this district prior to the introduction of the jasperoid, the latter being contemporaneous with the ore-bearing solutions.

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‡ References are to bibliography on page 134.

Location and Topography

The Tri-State district, shown by Fig. 1, is a nearly continuous ore-bearing region that extends from the vicinity of Springfield, Mo., to near Miami, Okla., a distance of about 100 miles, and varies in width from a few miles to more than 30 miles. The two principal mining centers developed within this area are the Joplin-Webb City field and the Oklahoma-Kansas (or Picher-Miami) field.

Relationship of Limestone and Chert

As is well known to all students of this district, the Boone limestone member of the Mississippian series is the principal ore-bearing formation.

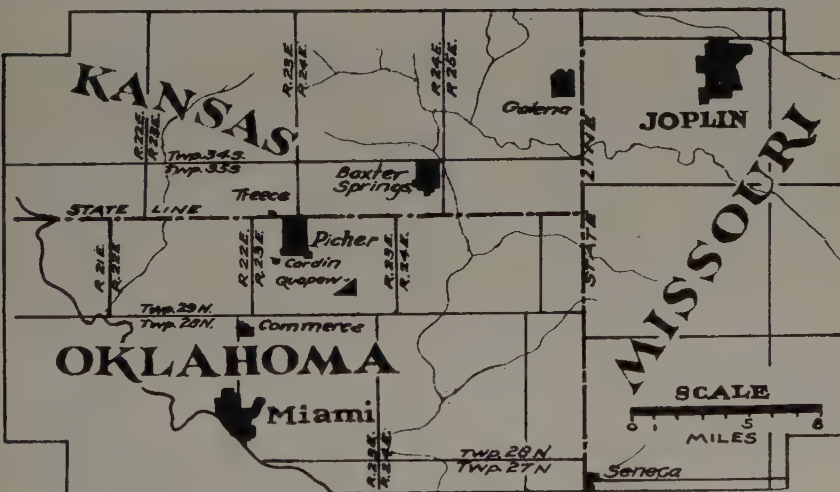

Fig. 1.—Index map of western part of Tri-State mining district.

The chertification of this formation furnishes the principal basis for the discussion of this paper, although some chert also occurs in the other limestone formations. The Boone, which evidently was originally deposited as limestone and is now composed of limestone, chert, dolomite, cotton rock, and in places tripoli, varies in thickness in this region from 200 to 400 feet, depending upon the extent of erosion.

It is probable, as would be expected, that small quantities of silica (from 0.1 to 1.0 or 2.0 per cent) were deposited syngenetically with this limestone, as practically every analysis shows a little silica. This is of minor importance to us, for our present interest centers in the great quantities of *introduced* chert that is so prevalent in the Boone in many places, in Missouri, Arkansas, Kansas and Oklahoma. In this district it is found in greater quantity per unit of volume than in any other like area with which we are familiar. The introduced variety is always

related to structural deformation which is as widespread as the chert. Messrs. H. A. Buehler and H. S. McQueen,[7] of the Missouri Geological Survey, have utilized many thousand insoluble residues, from numerous widely separated limestones, as a very successful means for identifying geologic strata, and they found silica in practically every sample that they examined from the Boone of this district.

At intervals during the past few years we have submitted numerous specimens from this district to others, particularly Messrs. Agar and Gregory, for independent study. Their work is still in progress but their present conclusions are stated separately as Parts II and III of this paper. Their comments regarding the two ages of introduced, or epigenetic, chert are of decided interest. We realized the epigenetic origin but did not distinguish between the two varieties. Now that the distinction has been made, first by Mr. Agar and then by Mr. Gregory, we submit a specimen, Fig. 20, collected several years ago, which shows brecciated chert cemented by a later chert. They have designated the two varieties as *Older chert* and *Younger chert*. The older is probably present in many places but is obscure; the younger is found in abundance throughout the district. The relative proportion of each is unknown. Both are Mississippian in age.

It is important to particularly note the fact that the *younger* chert cemented fragments of the *older* chert. This sequence of events at once removes the possibility of the syngenetic origin of the younger chert, the common type in this district. The brecciation and fragmental character of much of the *older* chert shows that it was subjected to deformation before *being cemented* by the *younger* chert. The two varieties were in turn brecciated by later deformations and recemented by the jasperoid ore and later minerals. Perhaps some of the differences of opinion regarding the origin of the chert are due to lack of study regarding the two varieties described in this paper.

Stratigraphy

Our study of the geology and ore deposits has revealed the Boone formation to be separable into several beds which are nearly uniform in thickness and have distinctive characteristics throughout the district. The detailed stratigraphic section, shown in Table 1, is the result of more than three years of intensive study of the Boone formation with constant subsequent application of the familiarity so gained to problems of economic importance. Partial to complete chertification of the limestone made the usual methods for identifying strata and datum beds nearly worthless. Accordingly, a method based solely on lithologic evidence and utilizing characteristic chertification of respective strata was devised which enabled us to determine datum horizons throughout the Boone as markers upon which to measure its detailed and general

structural geology. These markers were established from innumerable observations of churn-drill cuttings, surface exposures and underground workings.

The several beds shown in the following section are lettered for convenience up and down the alphabet from M bed which designates the *main* ore-bearing horizon in the Oklahoma-Kansas field and the bed with which we first became familiar. The letter M happened to be in about the right place to permit the range of the alphabet. To date B is the highest bed that we have found in the deformed, partly eroded Boone. Letter *I* was dropped because it is so easily confused with the numeral

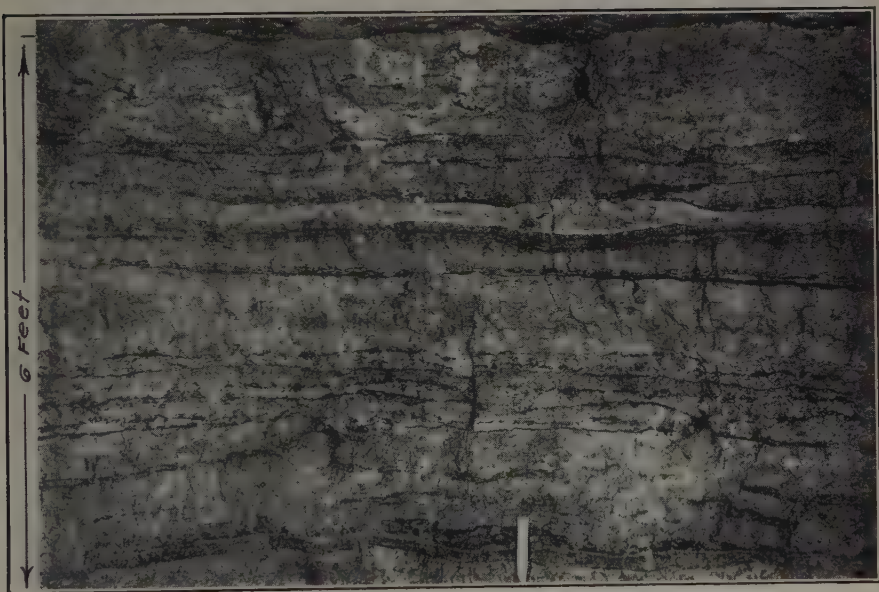

FIG. 2.—FROM G BED, LASALLE MINE, PICHER, OKLAHOMA.

Light bands are chert. This bed lacks the chert nodules so typical of K and M beds. Dark bands are jasperoid, sphalerite, and galena. It is impossible to differentiate them in this picture. Note the nearly vertical fracturing subsequent to the ore. In unaltered areas this is generally a thin-bedded limestone with numerous partings.

one. Beds below R have been unimportant to us and have not been used to date. Figs. 2, 8 and 10 show characteristic chertified strata in the ore-bearing horizons.

The strata in the Boone below Q bed consist of the Reeds Spring and Fern Glen formations, which are about 125 ft. and 30 ft. thick, respectively. They are generally barren but contain commercial orebodies in a few localities, particularly near Spring City, south of Joplin. The Reeds Spring chertifies in characteristic small, knotty nodules and often contains both cotton rock and chert. These nodules are bluish, brownish and grayish. The Fern Glen is usually grayish to greenish limestone, with little chert, and is shaly near the base.

TABLE 1.—*Stratigraphic Section, Boone Formation*

Bed	Thickness, Ft.	Characteristics
B	0–40 (depending on erosion)	Light brown and gray limestone and dolomite, some white and light blue chert
C	25–32	White and blue chert, brown and gray limestone and dolomite. Usually more dark blue chert in bottom 10 ft. of horizon Fig. 3, showing limestone, cotton rock and chert, is from this horizon
D	20–25	White cotton rock, some hard white chert, white and light brown limestone. Tripoli in this horizon where limestone has been leached. Contains commercial orebodies in a few mines
E	5– 8	Gray and brown chert and white chert nodules. Brown limestone and dolomite. Important ore bed in some mines contains mostly galena
F	12–15	Light brown limestone and white cotton rock. In areas of complete chertification is dense white and light gray chert
G	10–12	Important ore horizon in many mines. Ore occurrences in this and H bed are generally similar but this bed is more extensively mineralized. In some mines G and H beds both contain ore and are mined together Figs. 2 and 6 show chert development in this bed
H	13–15	G and H beds usually thin-bedded, alternating limestone and cherty bands 2 to 5 in. thick. In minable areas the ore bands are from ¼ to 2 in. thick and replaced similar thickness of limestone. The galena and sphalerite are usually banded with galena on top
J	4– 5	Brownish and gray limestone and chert, or soft greenish limy stratum usually containing glauconite. Mineralized only in areas of intense deformation. Bottom of Warsaw formation. Probably small unconformity
K	8–12	Top of Keokuk formation. Important ore bed. Comprises rounded nodules 5 to 9 in. in diameter in upper part of bed with long, larger nodules in lower part. Ore generally confined to upper two-thirds of bed. Short Creek oolite, 5 to 8 ft. thick, occurs in this horizon in some areas. Oolite is found from top of K bed to bottom of L bed Figs. 4, 5, 8, 9, 11, 12, and 13 show typical chert development in this bed
L	26–30	Massive limestone, massive grayish chert or cotton rock. Contains ore in zones of intense deformation. In places contains 5 ft. stratum of oolite Fig. 7 shows chert from this bed
M	19–22	One of the most important ore beds of Oklahoma-Kansas area. Where metamorphosed, definite nodules 4 to 12 in. in diameter occur throughout bed. In many places large nodules (6 to 12 in. thick by 2 to 5 ft. in dia.) at bottom of bed. Ore-bearing part of this bed in different areas of Oklahoma-Kansas field varies in thickness from 5 to 22 ft. Bottom 12 ft. is most productive horizon. Figs. 10, 15, 15*a*-1 to *a*-9, 17, and 20 show chert from this bed. Fig. 10 shows bottom of this bed and top of N bed in the Southside mine
N	20–25	Massive limestone, or mottled grayish chert with very few large (1 ft. thick by 5 to 15 ft. in diameter) nodules. Contains ore horizon 8 ft. thick near middle of bed in a few mines. Fig. 10 shows this bed chertified.
O[a]	8– 9	Important ore bed in a few mines. Round, flat nodules (2 to 4 in. by 3 to 6 ft.) embedded with cherty bands 1 to 4 in. thick. In some mines contains interbedded layers of nearly pure galena or sphalerite, or both, with galena above sphalerite, varying in thickness from a fraction of inch to several inches. These sheets of ore continuous in large areas. Such mineralization comprises "sheet ground" mines in old Missouri fields. Southern part of See-Sah mine, near Cardin, Okla., is in this bed and is in "sheet ground" formation
P[a]	8 -11	Large flat chert nodules interbedded in chert, generally barren, but in places mineralized with beds O, P, and Q, making ore horizon 30 to 38 ft. thick
Q[a]	17–18	Limestone and chert, generally massive. Only relatively few churn-drill holes have reached depths greater than 50 ft. below Q bed
R	55 +	Top of Reeds Spring formation. Largely dense limestone, dolomite or gray and blue chert, with chert nodules

[a] The Grand Falls chert horizon described by Smith and Siebenthal in U. S. Geological Atlas No. 148. *Joplin District Folio* (1907), is found only in or related to zones of deformation. In undisturbed areas it is limestone. It falls within the range of beds O, P and Q. Smith and Siebenthal give it a thickness of 15 to 120 ft. and state that "it lies about 100 ft. below the Short Creek oolite." The Short Creek oolite is found sporadically from the top of K bed to the bottom of L bed, a vertical range of 40 feet.

The stratigraphic section of the Boone formation, Table 1, is shown graphically by Fig. 18, which was selected because the several beds are easily distinguishable. Cuttings, as received from the driller, are washed in order to eliminate any dirt, then mounted on pine boards on a scale of 5 ft. to an inch. We have studied several thousand logs from drill holes that have been mounted in a similar manner.

Table 2 shows the character of the formations below the Boone according to a correlation by H. S. McQueen, Assistant State Geologist of Missouri, made from drill cuttings from a well drilled in 1930 at the Commerce Mining and Royalty Company's Bird Dog mine in the SE.¼, SE.¼, sec. 13, T.29N., R.22E., near Picher, Okla. This well is in an area of medium deformation and shows the intermediate stage of alteration and chertifica-

TABLE 2.—*Detail of Formations below the Boone*
By H. S. McQUEEN

System	Thickness, Ft.	Depth from Surface, Ft.	Characteristics
Pennsylvanian	100	0–100	Shale
Mississippian	315	100–415	Chert, limestone, and dolomite (Boone)
Ordovician	5	415–420	Brown, finely crystalline dolomite; sand grains; brown, white, and sandy chert; some dark green shale and pyrite
	5	420–425	Gray, finely crystalline dolomite; 40 per cent insoluble, sand grains, chert, and shale
	10	425–435	Light brownish gray, fine-grained sandy dolomite; dark brown quartzose and glassy chert, with associated fragments of sphalerite; also gray white chert
Cotter	25	435–460	Dense gray to brownish gray dolomite; fine-grained sand; white, gray, and brown chert; some pyrite and few fragments of sphalerite
	70	460–530	Gray, dense, fine-grained dolomite. Insoluble residues comparatively small, 5 to 35 per cent; considerable sand, 495 to 520 ft.
	320	530–850	Dolomite similar to above, with gray and blue-gray chert oolitic and banded to 585 ft.; below that depth, brown chert dominant. "Shines" of zinc at 680 ft.
Jefferson City	45	850–895	Dark brownish or bluish gray, finely crystalline dolomite. Insoluble residues small except 850 to 855 ft.; 40 per cent brown, sandy, and quartzose chert
Roubidoux	115	895–1010	Light gray, fine-grained dolomite; sandy in basal part, with some chert
Gasconade	150	1010–1160	Gray and bluish gray finely crystalline dolomite; insoluble residues up to 50 per cent contain chert
Van Buren	20	1160–1180	Blue-gray dolomite; insoluble residues contain chert; also sand and fragments of porphyry at 1180 ft.
Gunter	5	1180–1185	Dark gray finely crystalline sandy dolomite; insoluble residues 5 per cent contains: sand, fine, generally rounded and frosted grains; with chert white and sandy; also granite, bluish gray and red, both types kaolinized; pyrite
Pre-Cambrian: granite and possibly porphyry	10	1185–1195	Granite, red and bluish gray; latter finer grained and chloritic and possibly a rhyolite. Both contain pyrite and hornblende
	11	1195–1206	Granite, red, very coarse grained, with fragments of bluish gray, like above. Pyrite

tion. All of the pre-Chester formations contain small quantities of chert. We attribute the abundance of chert in the Boone to favorable reservoir conditions for the introduced silicic acid.

Metamorphism

The Boone was deposited as limestone in conformable horizontal strata. Megascopically it is fairly coarse in texture, grayish to brownish, and very similar in appearance throughout. It was chertified where structural deformation formed channelways and favorable reservoirs which permitted circulation of silicic acid solutions and precipitation of the silica as chert. A gradational variety known as cotton rock, which is

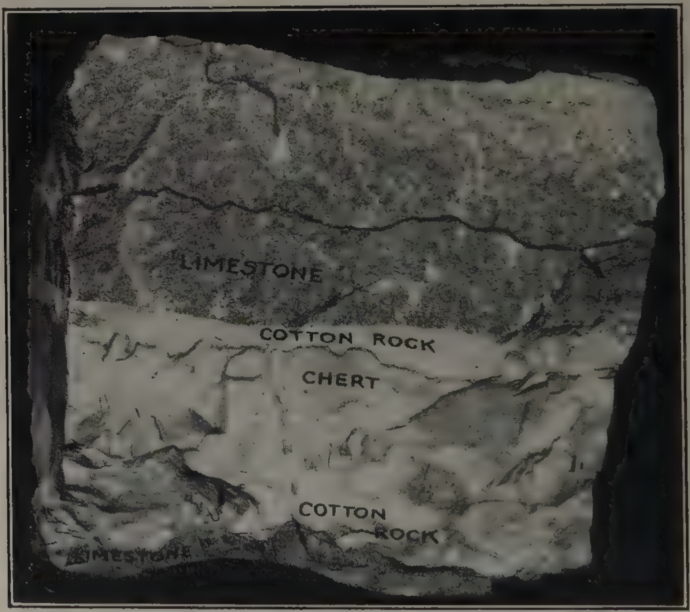

Fig. 3.—From C bed, Big John mine near Treece, Kansas. Three-fourths natural size.

Typical of C bed in zones of medium deformation. Compare this chertification with that shown in Figs. 4 and 5.

a partly chertified and thoroughly impregnated limestone, predominates between the two extremes of chert and limestone. At one extreme cotton rock grades into tripoli (a variety of cotton rock) and at the other into chert. The boundaries between these extremes and between masses of each material are often very irregular. Undoubtedly they are influenced by physical and chemical characteristics in the several limestone strata, by bedding plane and stylolite partings which were opened by stresses, and by the manner of infiltration of the silicic acid solutions. Our observations show that all of the chertification in the Tri-State district has a

definite relationship to the structural deformation of the strata in which it occurs.

The chertified zones vary greatly in size and shape; some follow shear zones, vertical to flat dipping, which vary in width from a few inches to several hundred feet, and in length from a few inches to a mile or more; some consist of intercalated chert bands in limestone, the chert replacing limestone strata that vary from an inch to 30 ft. or more in thickness,

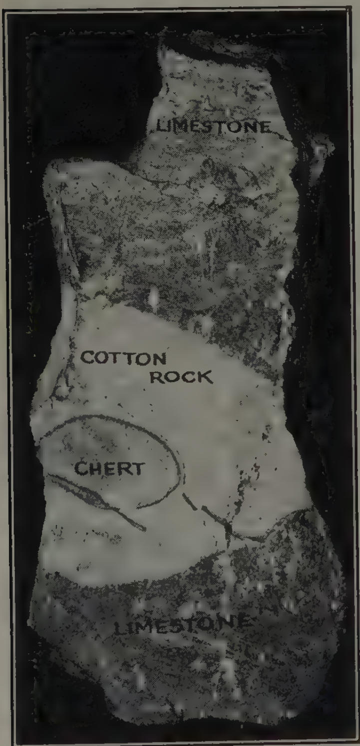

Fig. 4.

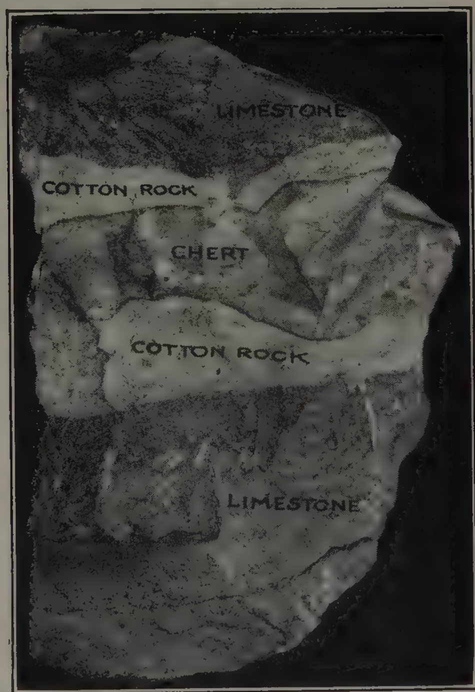

Fig. 5.

Fig. 4.—From K bed, Goodwin mine, Picher, Oklahoma. Three-fourths natural size.

Apparently chert or cotton rock phases are due to the quantity and kinds of acid present. Thus in and contiguous to many shear zones the gradation is chert, cotton rock, and limestone, respectively, as the distance from the centers of infiltration increases.

Fig. 5.—From K bed, Goodwin mine. Three-fourths natural size.

Same as Fig. 4, except that nodule is shown lengthwise. Compare Figs. 4 and 5 with Fig. 3.

with areas from a few square feet to many acres; and some are irregular masses in the limestone with volumes from a few cubic feet to many hundred cubic feet. Chertification is common in all formations from the top of the Boone to the granite basement.

The chertification is pre-Chester in age, as attested by the fact that

the Boone was deformed and chertified in some degree from top to bottom in these earlier zones of deformation, whereas the Chester (having been deposited later) is free from chertification. Silicification, which apparently is connected with the ore-bearing solutions, is found in the Chester above some of the orebodies in the Boone. The Chester also contains grains and pebbles of chert derived from the Boone, as noted by Samuel Weidman[10] in his paper on this district.

Fig. 6.—From G bed, Goodwin mine. Three-fourths natural size. Typical replacement of limestone (dark gray) by chert (light). Black areas are sphalerite. This specimen is unbrecciated.

The chert ranges in color from white to dark gray, brown and blue, and in appearance and texture from dull and chalky to vitreous. A single small piece may show many of these characteristics. Many small nodules and concretions, of various colors, with massive chert centers are enclosed within halos of cotton rock of lighter color. Figs. 3, 4 and 5 show the gradation from limestone, through cotton rock, to chert.

Chert nodules and concretions of many shapes and sizes, so characteristic of some of the limestone strata, particularly beds M and K, are obviously due to infiltration of silicic acid solutions. Some of the char-

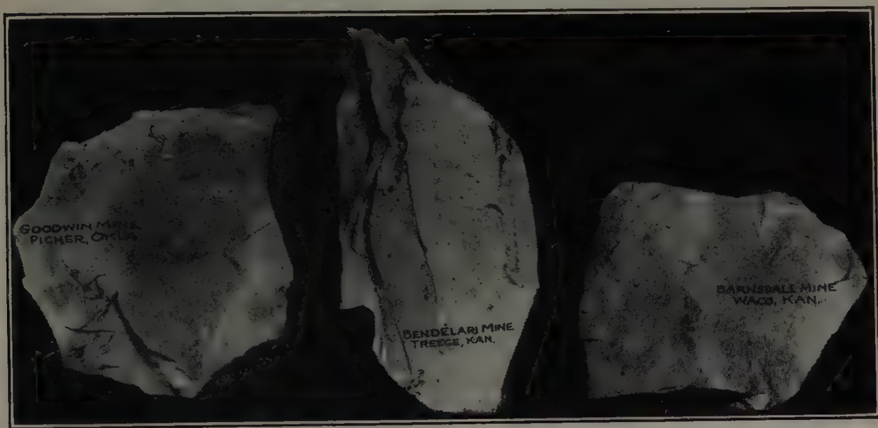

FIG. 7.—TYPICAL L-BED CHERT, TRI-STATE DISTRICT. THREE-FOURTHS NATURAL SIZE.

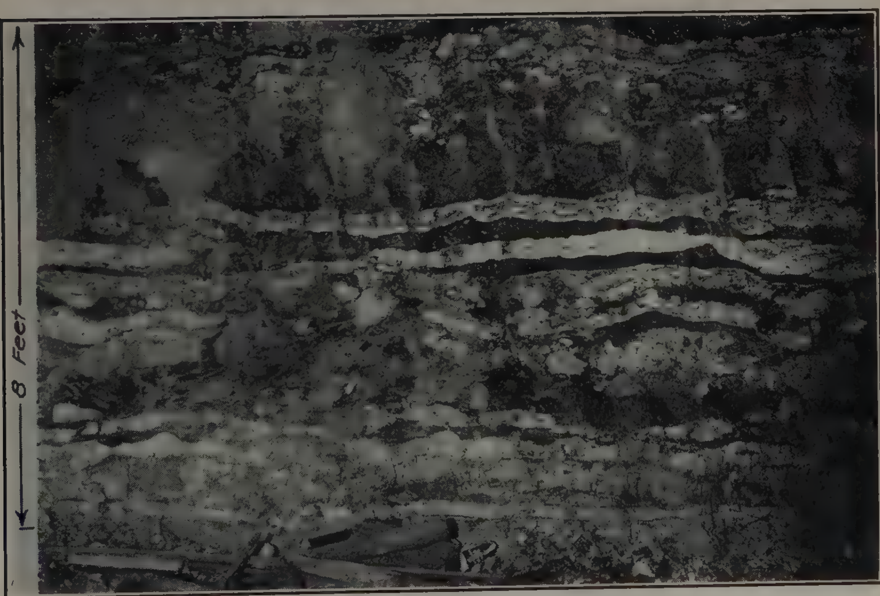

FIG. 8.—FROM K BED, GOODWIN MINE.

A common condition where this bed is ore bearing in zones of medium deformation. Note various shapes of nodules (white) of chert and cotton rock. The long bands are generally only partly chertified and contain numerous small chert or cotton rock nuclei. The dark material is jasperoid.

acteristic ones are shown in Fig. 12; those in M and K beds are similar but the latter are generally smaller. They occur as near spheres of less than an inch to a foot in diameter, and as circular masses from a few inches

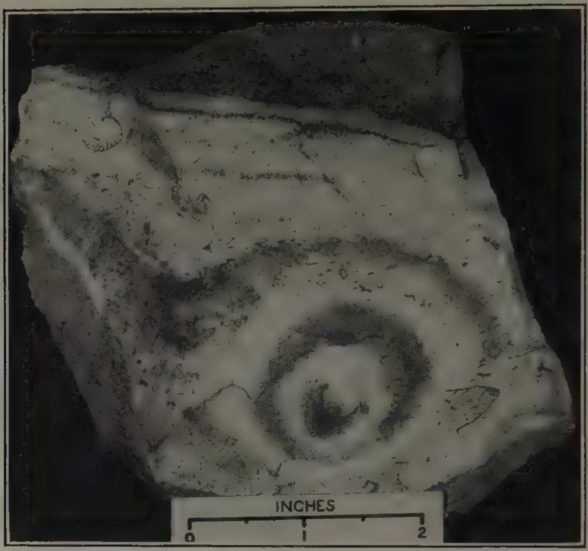

Fig. 9.—From K bed, Goodwin mine.
Large zoned chert nodule showing chertified fossils.

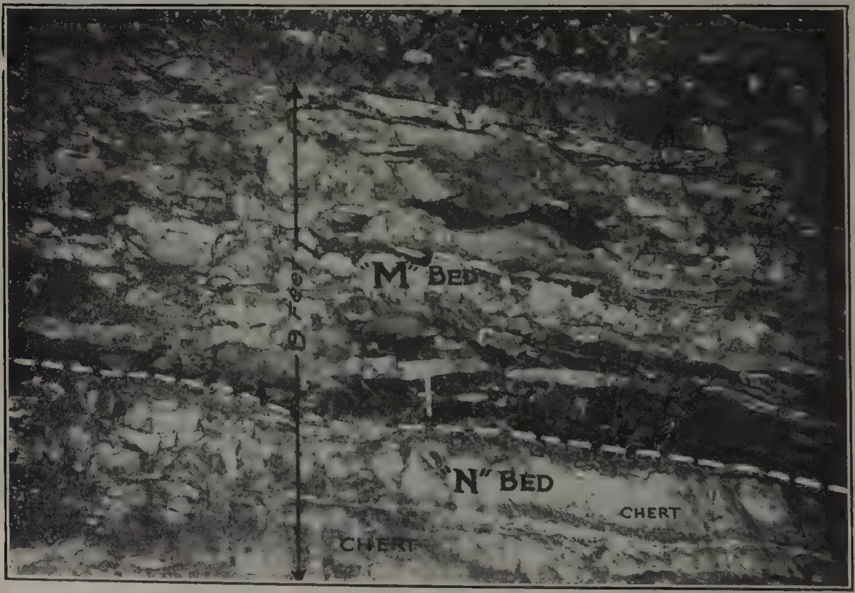

Fig. 10.—From M and N beds, Southside mine near Commerce, Oklahoma.
All of the strata are dipping towards a shear zone. Note development of chert nodules in M bed and absence of them in N bed, which is completely chertified in the picture. Dark material in M bed is jasperoid and sphalerite. M bed is principal ore horizon in Oklahoma-Kansas field.

to several feet in thickness with horizontal dimensions of 5 to 30 ft. or more. Fig. 11 shows the development of nodules in limestone.

Stylolite partings and similar channelways were particularly favorable avenues of ingress for the silicic acid solutions. They greatly aroused our interest when we realized their relationship to the chertification in the Boone. They are found in limestone and calcareous shales in many parts of the world, and have been described by numerous writers whose opinions differ regarding their origin. By many they are thought to have been formed by differential vertical settling along irregular bedding

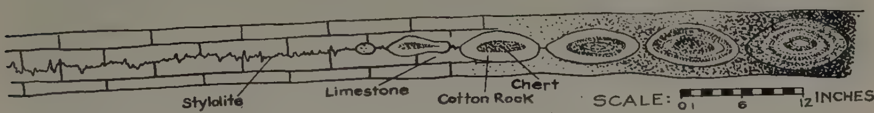

FIG. 11.—FROM SKETCH MADE UNDERGROUND, K BED, GOODWIN MINE.
Stages in development of chert nodules in limestone. On right, limestone, which borders small shear zone, has been completely chertified and chert nodules are fully developed. On left, limestone is little altered, and nodules of chert and cotton rock (as a halo), which occur along a stylolite, become smaller and gradually disappear.

partings where solution was unequal. In this district they roughly parallel bedding planes and separate in a general way coarsely crystalline from fine-grained limestone. However, some are found trending at a steep angle across the strata and across other stylolites that follow the bedding planes. Stylolites are common in the marble, from the Carthage and Joplin quarries, that is used in buildings in Joplin and elsewhere. These quarries are in the Boone.

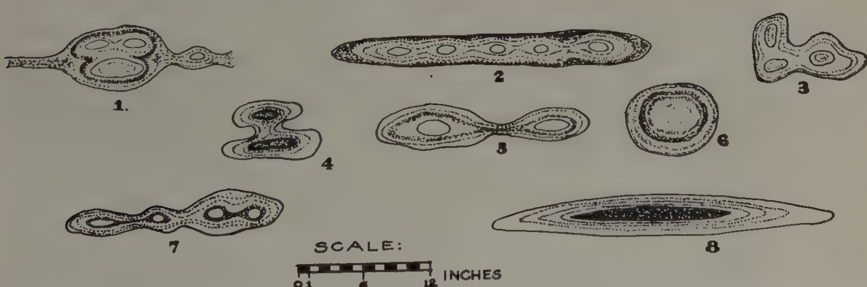

FIG. 12.—NODULE TYPES IN K BED, TRI-STATE DISTRICT.
Nodules may be cotton rock or chert, or both, as illustrated by Figs. 4 and 11.

The greater part of the chert was formed beneath the limestone surface—some near, some many hundred feet below. A small part of it may be of surficial origin. The areas, or masses, of chert are interrupted vertically and laterally by unaltered or partly altered limestone and indicate numerous centers of siliceous emanations related to the structural deformation. The line of demarcation between limestone and chert is very marked in some places and in others is gradational through cotton rock.

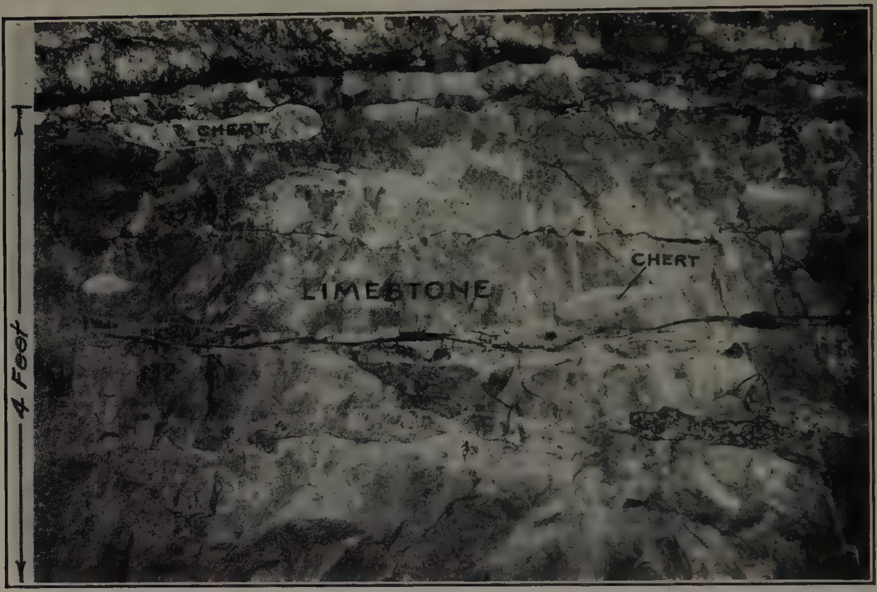

FIG. 13.—FROM K BED, BENDELARI MINE, TREECE, KANSAS.

This picture was taken in the center of a zone of little disturbance midway between two parallel shear zones and about 100 ft. from each. Note that only a few nodules have formed in the limestone and compare with Fig. 8, which shows the development of nodules on the edge of a shear zone.

FIG. 14.—CHERTIFIED FOSSIL IN CHERT. THREE-FOURTHS NATURAL SIZE.

Fossils of this size and larger are common in some Boone areas. Many fossils lose their identity after chertification.

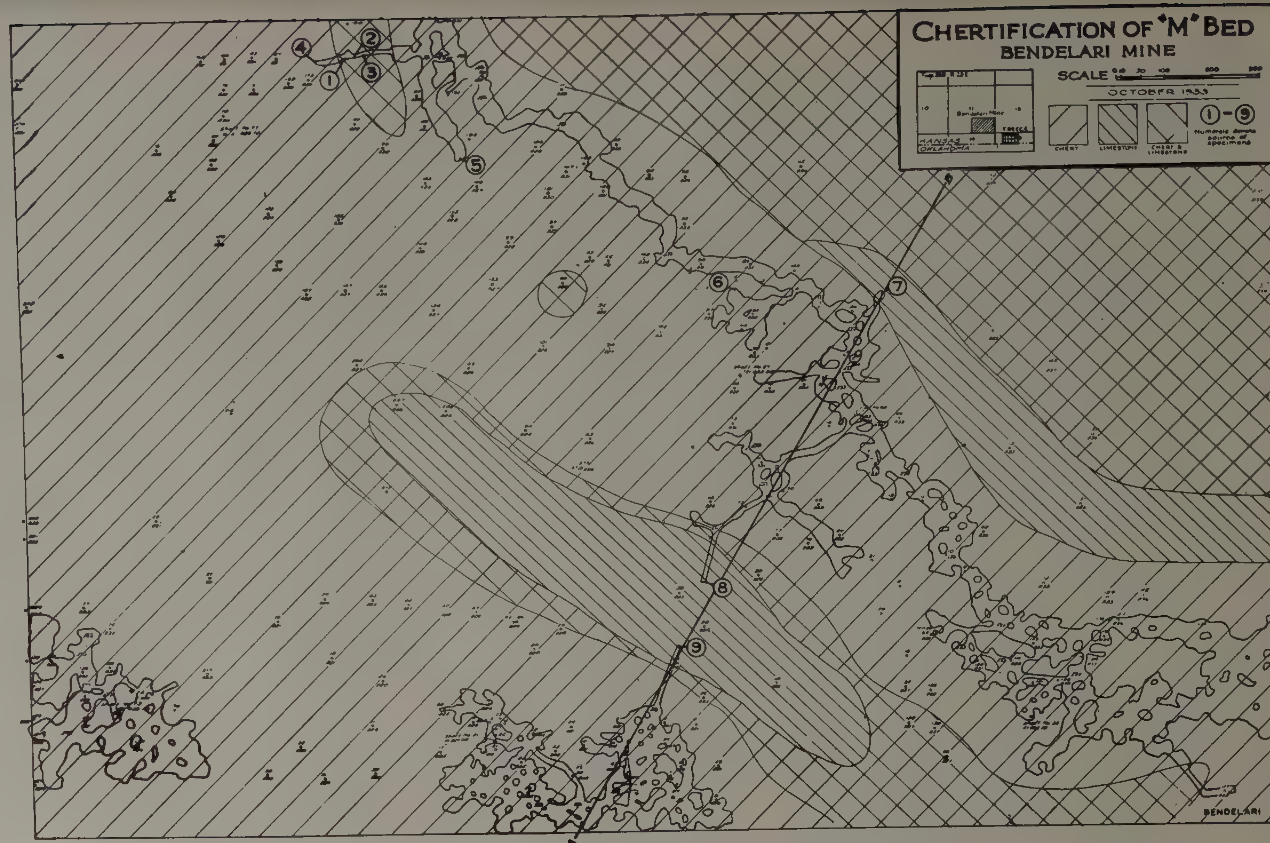

FIG. 15.—SUBSTRATUM MAP OF M BED, BENDELARI MINE.

The numerals 1 to 9 refer to specimens shown in Figs. 15-*a*1 to *a*-9, which were collected at the points designated, and studied in detail in preparing this paper.

The northerly mine workings are in a strong shear zone which is an important ore reservoir in this bed and particularly in K bed, 50 ft. vertically above.

Notice limestone, cotton rock and chert areas, then refer to description of specimens from these localities.

The interested observer may study the characteristic relationship of limestone, chert and cotton rock to geologic structure in the drifts in M bed on the bottom level of the Bendelari mine in the SE.¼, sec. 11, T.35S.,

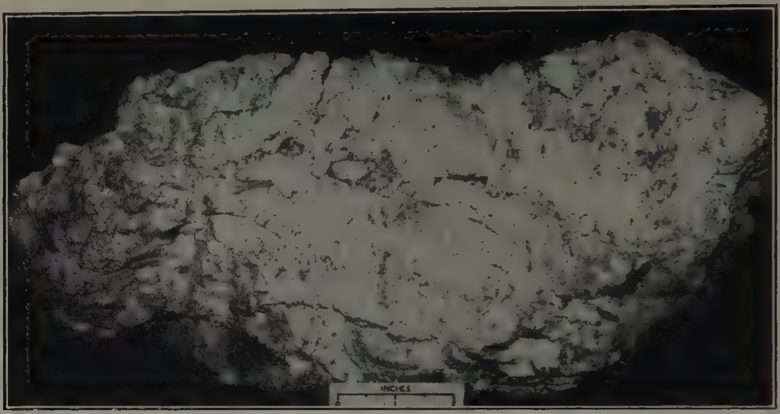

FIG. 15a-1.—FROM EASTERLY EDGE OF STRONG SHEAR ZONE IN HAULAGE DRIFT, M BED, BENDELARI MINE. COTTON ROCK AND CHERT BRECCIA CEMENTED WITH CALCITE AND PINK DOLOMITE.

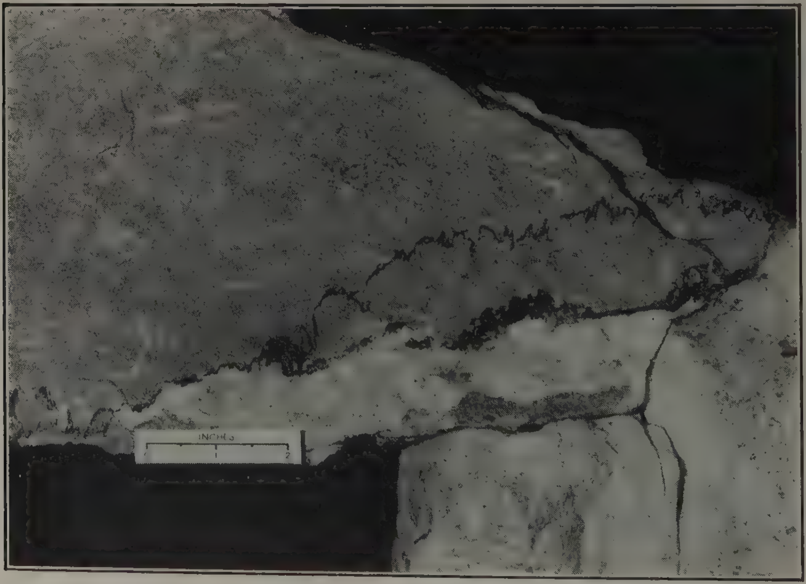

FIG. 15a-2.—FROM M BED, BENDELARI MINE, 22 FT. EAST OF SPECIMEN IN FIG. 15a-1. From location of specimen 15a-1 to a point 90 ft. east, haulage drift penetrated zone of very little deformation, in which M bed is mostly limestone; whereas in shear zones on either side limestone is largely replaced with chert. This specimen shows relation of stylolite to chert and also incomplete replacement of limestone.

R.23E., in Kansas; in several drifts in the eastern part of the Cherokee mine; in the long southerly drift in the Barr mine near Treece, Kansas; in drifts westerly from the mine workings into tight limestone in the

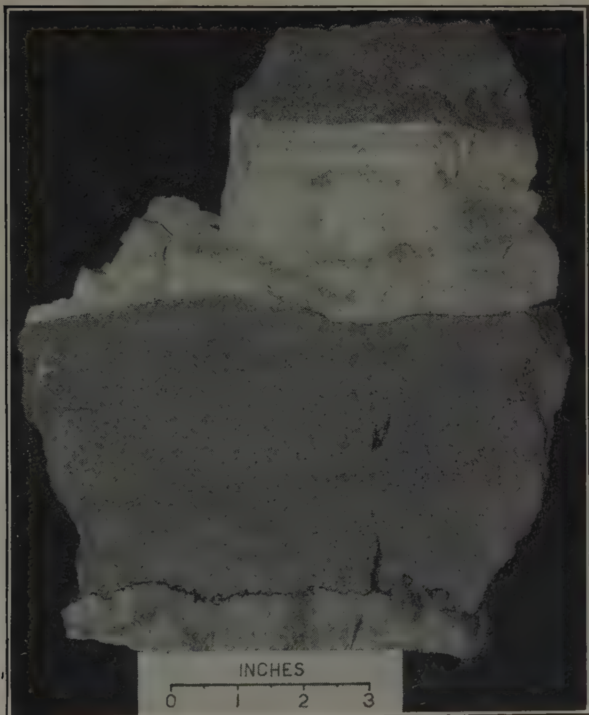

FIG. 15a-3.—FROM M BED, BENDELARI MINE, 20 FT. EAST OF SPECIMEN IN FIG. 15a-2. Shows chert nodule in limestone (at top), and replacement of limestone by chert along stylolite (at bottom).

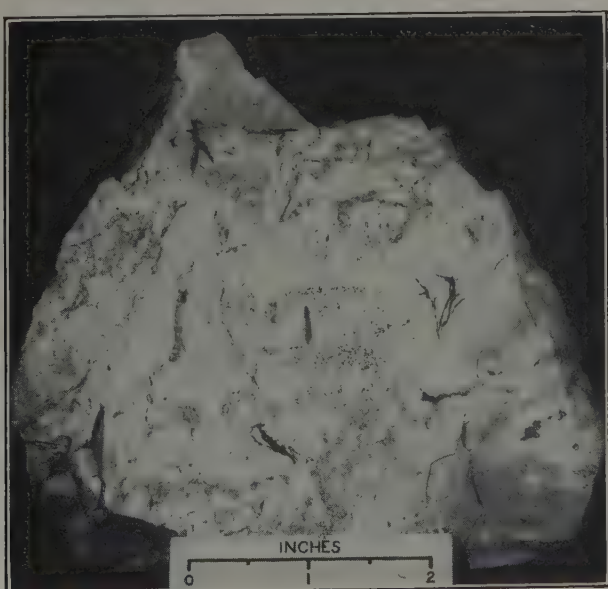

FIG. 15a 4.—FROM M BED, BENDELARI MINE, 57 FT. WEST OF SPECIMEN IN FIG. 15a-1. In chertified shear zone showing cemented chert breccia.

FIG. 15a-5.—FROM DRIFT IN OREBODY IN SHEAR ZONE, M BED, BENDELARI MINE. Chert with jasperoid, sphalerite, pink dolomite and calcite.

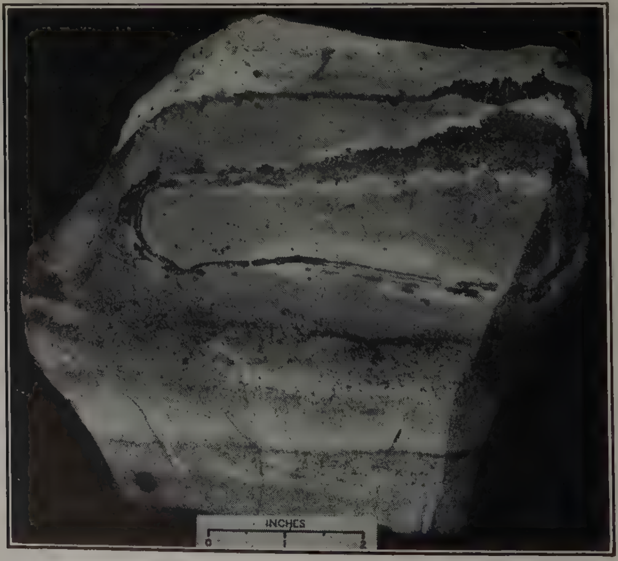

FIG. 15a-6.—CHERT NODULE FROM M BED, BENDELARI MINE, SHOWING CONCENTRIC BANDING, FROM DRIFT IN OREBODY IN SHEAR ZONE.

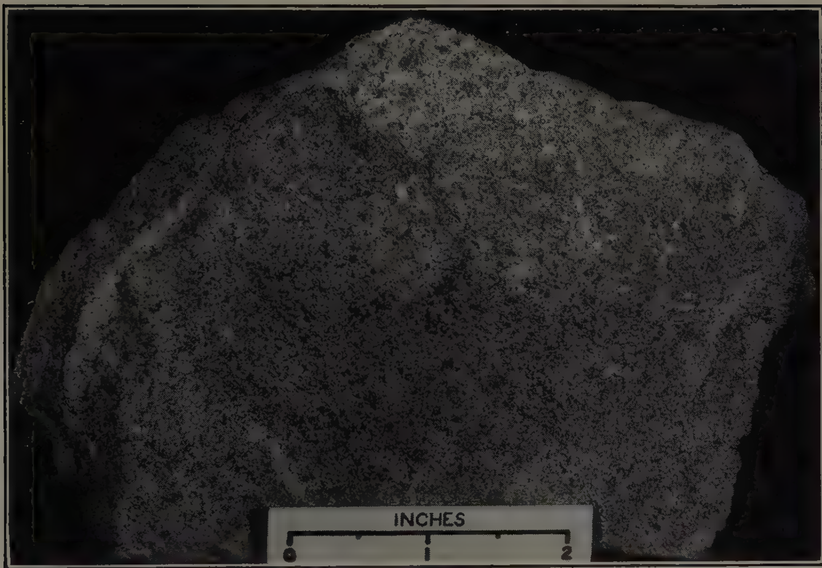

FIG. 15a-7.—TYPE OF LIMESTONE IN M BED, BENDELARI MINE, IN AREA WHERE CHERTIFICATION CONSISTS OF A FEW NODULES ALONG STYLOLITE AND BEDDING PARTINGS. Specimen was taken from haulage drift at point 40 ft. from chertified shear zone.

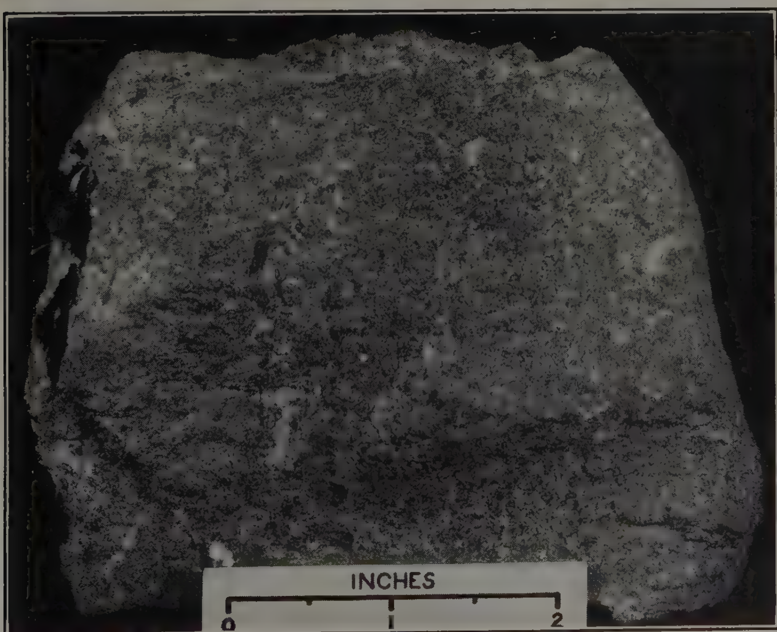

FIG. 15a-8.—LIMESTONE FROM HAULAGE DRIFT, M BED, BENDELARI MINE, IN AREA IN WHICH NO CHERT NODULES CAN BE SEEN.

Evans-Wallower No. 7 mine near Cardin, Okla.; and in many other places throughout the Oklahoma-Kansas mining field.

Nearly all of these drifts are in M bed, but other beds in the Boone strata show similar characteristics. M bed is cited because it is the principal ore horizon in the Oklahoma-Kansas field and the underground workings therein are more widespread, and the openings are now accessible in all of these mines, except the Cherokee. Fig. 13 shows partly developed nodules in limestone in a drift in K bed in the Bendelari mine. This identical stratum is largely chert in the ore-bearing shear zones at the ends of the 200-ft. drift in which the picture was taken. Fig. 15 shows

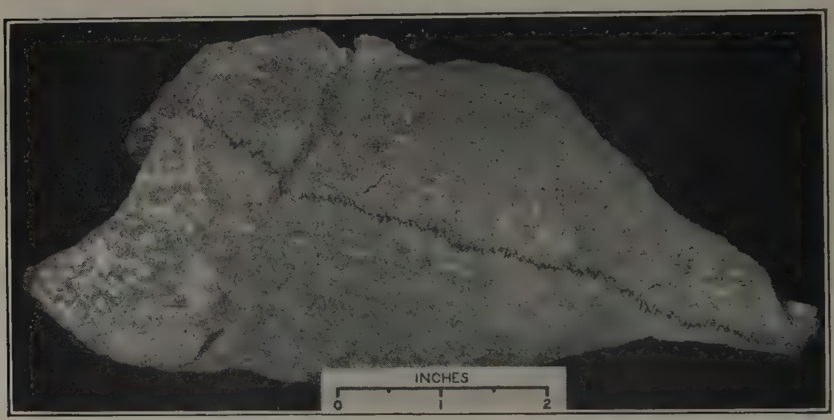

FIG. 15*a*-9.—LIMESTONE SHOWING STYLOLITE, M BED, BENDELARI MINE.
This specimen was taken at point 150 ft. from specimen in Fig. 15*a*-8. There are no nodules in area from which these two specimens were taken.

the substratum geology in the middle of M bed and Fig. 16 is a vertical section through this mine on line *A-B*.

It is our observation that tripoli is formed by the leaching of limestone from cotton rock, which is partially chertified limestone, through the agency of circulating solutions. The resulting product is nearly pure silica and is very light and porous. Small quantities of tripoli are found in all parts of the Boone, in zones of deformation. It is particularly abundant in D and F beds. The best underground deposit that we have observed is in F bed in the Northern mine, near Treece, Kansas. Workable deposits of tripoli are found at several points in the Ozark region. Some of the largest and best in the United States are sporadically distributed over a number of square miles in Missouri and Oklahoma near Seneca, Mo., 15 to 20 miles south of Joplin, and have been exploited extensively for many years. They occur in several beds in the Boone probably D, E and F described in Table 1. The minable tripoli is near the surface, lies nearly horizontal, and is from 5 to 12 ft. thick. It is overlain by several feet of angular gravel, or surface soil, and is

generally associated with small quantities of massive chert, frequently as nodules, which are picked out by hand.

Limestone, which is generally crystalline, is common throughout the district in great volumes, but is usually limited to some of the more massive beds of the Boone, as chert or cotton rock is found in one or more strata everywhere in the district. At the limestone and marble quarries near Joplin, Carthage, Springfield, and elsewhere, the workable beds of limestone, 5 to 50 ft. thick, have strata containing chert above or below them. Churn-drill holes, throughout the district, here and there show similar interbedding. The extent of the limestone within these interbedded strata varies from a few square feet to several hundred acres. The maximum limits are unknown for lack of exploration. Occurrences of similar limestone are found throughout the Oklahoma-Kansas field, which is a unit area of intense structural deformation. Here, as is to be expected, the areas of limestone are smaller but some of them cover many acres and gradually grade into chert on all sides in the same strata. What is probably the largest limestone area of this type within the limits of this particular field, is located in the SW.¼, sec. 18, T.29N., R.23E., in Oklahoma, and comprises parts of the Pelican and Foch (Ton-gah-hah) leases. Smaller similar areas are very common, one of them in the Bendelari mine already mentioned. A substratum map of this mine, showing the geology of M bed, and a vertical section across this property, are included with this paper as Figs. 15 and 16 and are largely self-explanatory.

The introduced silicic acid acted differently upon different limestone

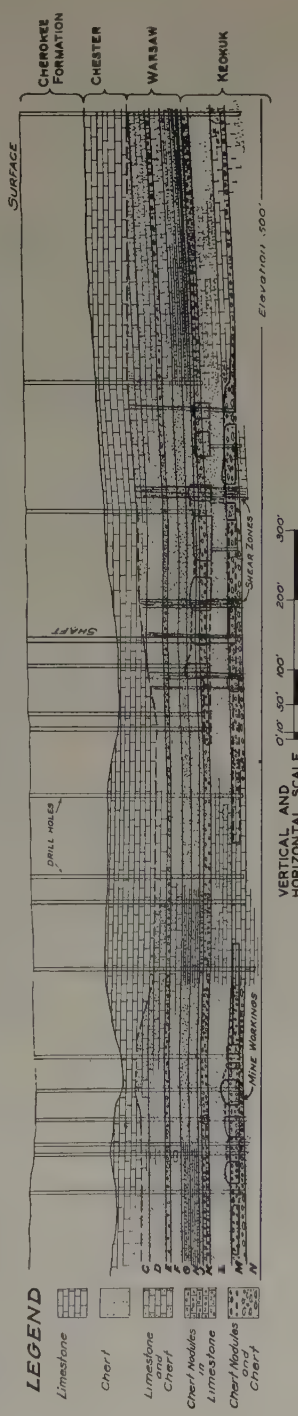

FIG. 16.—VERTICAL SECTION ON LINE *A-B*, M BED, BENDELARI MINE.
To be used in connection with Fig. 15.
Notice nearly vertical shear zones, which do not penetrate the Chester, and the limestone zones between the two drifts in M bed.

strata and brought out characteristics that made them readily distinguishable over many hundred square miles. These characteristics apparently are due to inherent physical and chemical properties of the respective strata. Beds K and M, and others to a lesser degree, developed nodules or concretions ranging in diameter from a few inches to 12 in. aligned in roughly parallel bands. Bed L became massive chert throughout its width of 30 ft. and rarely contains nodules. Beds G and H developed chert in long, parallel bands 2 to 8 in. thick, as shown in Fig. 2. In the Oklahoma-Kansas field these two beds chertified more readily than any other part of the Boone within the range of the mine workings, and many of the churn-drill holes show the chert in these strata to be more widespread than in strata above or below them. This is due probably to their thin-bedded characteristics, which permitted them to be deformed more readily than thick, massive-bedded limestones.

Fig. 17.—From M bed, Bendelari mine. Three-fourths natural size.
Chert cementedwith jasperoid. This is a common type of breccia throughout Oklahoma-Kansas field.

In the Joplin-Webb City field, beds O, P and Q have been designated by earlier geologists as the Grand Falls chert or "sheet-ground horizon." It is continuous, comprising limestone in undeformed zones, and chert in zones of structural deformation. The gradation from chert to limestone is dependent upon the distance from the centers of deformation. The so-called Grand Falls chert, 8 to 30 ft. thick, sometimes covers many acres and was an important ore horizon in the old Joplin-Webb City field. It is ore-bearing in the See Sah, Ballard, and Hartley mines in the Oklahoma-Kansas field. In the ore horizons the chert and ore occur as intercalated bands, the former from 2 to 8 in. thick and the latter from ½ to 3 in. thick.

Nodules and concretions are common phenomena of the entire district and of many other parts of the Ozarks. Underground they are abundantly exposed in K and M beds. They have a common origin and differ in

shape only because of the difference in character of the host rock and the manner of infiltration of the silicic acid solutions. By numerous observations it has been possible to trace their obvious origin. They developed by first forming small dense chert or cotton rock nuclei in limestone. With the addition of the precipitate the nodules increased in size and generally developed in concentric layers of either chert or cotton rock. The chert nodule is usually in or near centers of deformation, whereas the cotton rock type is nearer the outer limits. Between these extremes are found the nodules with chert centers enclosed in a banding or a halo of cotton rock such as Figs. 3, 4 and 5 in this paper. Not only does the degree of chertification in the nodules vary with the distance from the centers of zones of deformation, but their quantity and size also diminish. Following nearly completely chertified strata, in which chert nodules are abundant, from zones of structural deformation into undeformed limestone, the proportion of chert in the bed as a whole gradually peters out, and the nodules become smaller and smaller and more infrequent, and at last disappear entirely. The distance necessary to complete such a cycle varies greatly. In this district it was completed, in some cases, within 300 feet.

The readily observed physical characteristics which distinguish the several limestone strata, both in surface and in underground exposures, as revealed particularly in polished surfaces, show them to be of three general types. Beds G and H are lamellar with numerous stylolite and depositional partings; K, M, O, P and Q have fewer of both; and L is massive

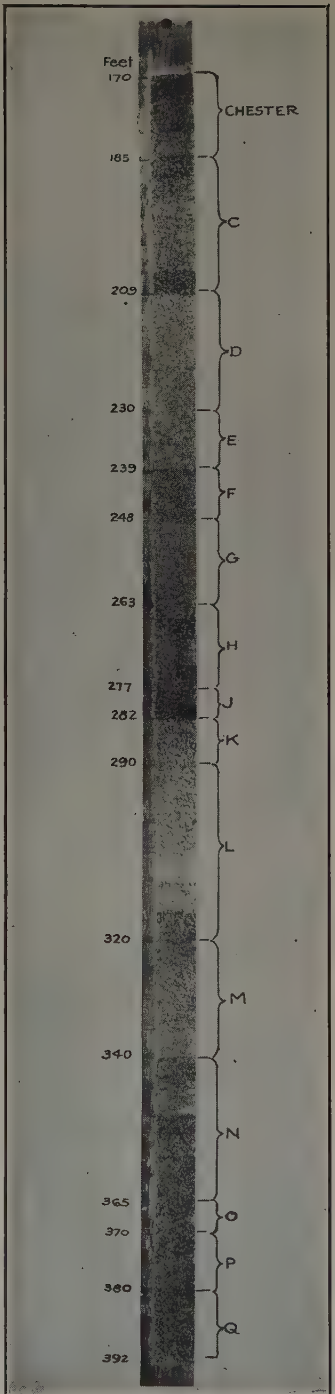

FIG 18.

FIG. 18.—MOUNTED DRILL-HOLE CUTTINGS FROM BIG JOHN MINE CHURN-DRILL HOLE No. D-55. SEE TABLE 1.

with widely separated partings. Stylolite partings occur at various angles to the bedding planes, some being even at nearly right angles. In the Wilson mine near Cardin, Okla., nodules were noted aligned with a shear zone cutting steeply across the bedding.

Conclusions

We have already discussed the age of the chertification and stated our reasons for designating it as Mississippian. As yet we have insuffi-

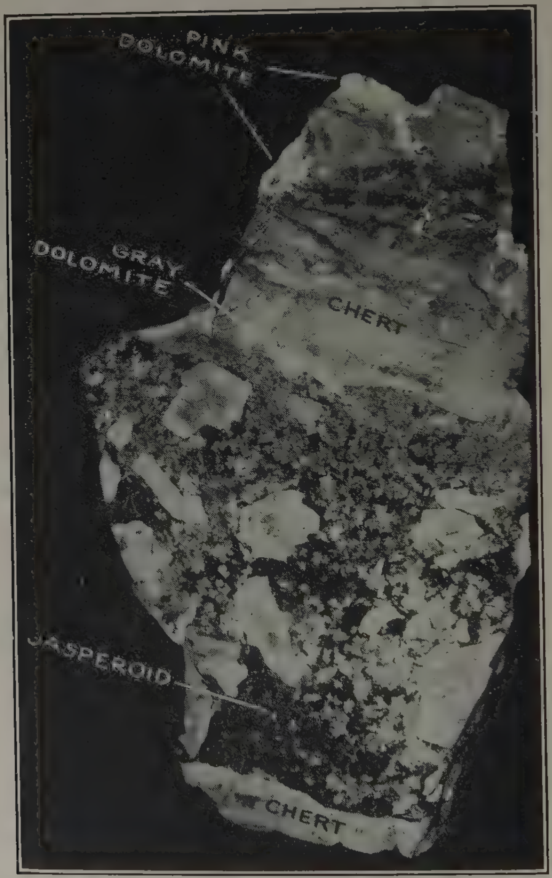

Fig. 19.—From G bed, LaSalle mine. Three-fourths natural size.
Chert and chert breccia cemented by gray dolomite, which later was partly replaced by jasperoid. The light colored mineral near the top of the specimen is pink dolomite. See page 129.

cient data to determine the age of the ore deposits, except to say that they are post-Pennsylvanian, as this formation is silicified and contains jasperoid, galena and sphalerite in some of the zones of structural deformation.

The preceding part of this paper is based almost exclusively upon our actual observations regarding chertification. It seems extremely prob-

able to us that others, having made the same observations, would reach similar conclusions. Our intensive study together with our scattered observations elsewhere in the Mississippi Valley where chert is common leave us no choice but the conclusion that the chertification was localized by structural conditions that provided channelways for the movement of waters charged with silicic acid from some abundant source. As to where it all came from, we too would like very much to know. We merely feel sure that it was introduced from elsewhere and replaced material that previously was limestone. It seems most likely that it came from the same general source that yielded the ore deposits and as yet we see no reason to believe that these are not of hypogene origin.

The cycles of mineralization comprising chert, gray dolomite, jasperoid and ore, and later minerals deposited in sequence in the same general zones of structural deformation. Some of these minerals are shown in Fig. 19 and other figures.

Apparently the chert or cotton rock phases are due to the quantity and kind of acid present. Where silicic acid was abundant chert predominates, where it was less abundant cotton rock predominates. Thus in and contiguous to many shear zones the gradation is chert, cotton rock and limestone, respectively, as the distance from the centers of infiltration increases.

Theories Regarding the Origin of Chert

Numerous theories have been advanced for the origin of chert. George R. Mansfield[6] gives an excellent summary of these theories. He says:

> Barton,[1] in referring to the Mississippian chert in the vicinity of St. Louis, states that the theories suggested for the formation of chert are essentially six, of which three ascribe the chert to organic sources and three to inorganic sources. These theories are stated as follows:
>
> 1. The chert is composed of formerly colloidal silica that was derived from the decomposition of siliceous sponges and other siliceous organisms that collected in depressions on the ocean floor. The bands of chert represent former sponge beds where the sponges remained in place and accumulated over a considerable area.
>
> 2. The chert was formed before the consolidation of limestone through the solution of scattered siliceous spicules and the almost immediate replacement of parts of the limestone.
>
> 3. The chert was formed after the consolidation of limestone through the solution by percolating waters of siliceous spicules and the replacement of part of the limestone by this dissolved silica.
>
> 4. The chert was formed by the precipitation of silica and the replacement of limestone in the presence of circulating waters which have passed through sandstone, arenaceous rocks, or rocks containing silicates.
>
> 5. The formation of the chert was due to the reaction of dissolved silica in sea water with limestone with the consequent precipitation and possible later concentration of the silica.

6. With the diffusion of silica in solution through limestone, concentration will vary in the direction of diffusion, and deposition, which results when concentration is sufficient, will be in zones perpendicular to the direction of diffusion. As the conditions of diffusion were more favorable in the early days of consolidation, and as the most likely direction is upward toward the surface or downward from it, deposition will be parallel to the stratification, although independent of it. The development of chert in successive zones is due to the lowering of concentration immediately around the first started zone or zones of crystallizing material. The silica may be derived from organic or inorganic sources.

To the above six should be added the theory of C. K. Leith,[(5)] who regards "the Grand Falls chert as an old erosion surface . . . " This is an untenable hypothesis, as was pointed out in answering Dr. Leith in our paper previously cited, and in discussing O, P and Q beds (Grand Falls chert) in this paper.

Dr. W. A. Tarr, of the University of Missouri, who is one of the chief exponents of the syngenetic origin of chert, has published in the August, (1933) number of *Economic Geology* a paper entitled "The Miami-Picher Zinc-Lead District." He says:

> This article is written to take issue with the authors (Weidman[(12)] and Fowler and Lyden[(3)]) on their interpretation of the age and origin of the chert; also, to point out that to regard this chert as an original chemical deposit, formed simultaneously with the limestone of the Boone formation, makes possible a clearer, more logical, and more accurate account of the origin of the ores.

His discussion covers " . . . first, the origin of the chert, (not the jasperoid), second, the origin of the chert breccias associated with the ores, and, third, the origin of the jasperoid and zinc-lead ores."

A large part of Dr. Tarr's paper comprises numerous unsupported statements expounding his and others' theories regarding the origin of the chert and chert breccias, which carry little weight, even though he says:

> . . . the writer's notes show that he favored this method of origin of the breccia over twenty years ago, even before his intensive study of chert, and a similar method of origin has been advocated by others,

and that his

> . . . studies of chert, especially of the larger nodules and lenses, have revealed that these silica aggregates are in a constant state of stress as they exist in the rocks. . . . On the removal of the surrounding rock, this internal force becomes effective and aids in the mechanical disintegration of the chert mass.

Since we are not particularly concerned with Dr. Tarr's theories, we shall confine our discussion of his paper to some conflicts between his statements and our actual field observations. It should be evident to anyone who bases his opinions upon actual studies of geological conditions in the field that structural deformation, rather than solution, is primarily responsible for most of the chert breccia in this district. Dr. Tarr, being unfamiliar with the important structural features of the area and their relation to the chertification and the localization of the orebodies, takes

the liberty of minimizing or ignoring them. His lack of acquaintance with the facts can alone be responsible for such statements as he makes on page 474, i. e.:

> Faulting has had little to do with the localization of these galleries and shafts . . . Strong major joint systems were apparently absent, as little alignment or definite arrangement of the orebodies is noted in the maps representing them. The writer does not regard the various tension shear zones, postulated by Fowler and Lyden, as at all essential.

The positive identification of the beds of the Boone formation throughout the Tri-State district is, of course, the basis for any real knowledge regarding structural deformation. The significance of the detailed stratigraphy of the Boone is so great that it cannot be ignored by anyone presuming to understand or have an opinion about the structure and alteration of the formation.

A practical knowledge of the stratigraphy has enabled us to measure flexing and faulting in the beds and to establish the fact that every orebody in the Oklahoma-Kansas field is definitely related in some manner to structural features which have resulted from deformation. Adjustment by shearing and flexing is evident throughout the entire district, and in parts of it the structural displacement exceeds 350 ft. vertically, as evidenced from a structure map compiled from many thousand observations. These are facts about which it is unnecessary to elaborate further.

On page 465 Dr. Tarr says: "Fowler and Lyden . . . state that outside of the disturbed areas 'little or no chert is found.' They regard the Boone formation outside the Tri-State district as being free from chert, a conclusion that shows they are unfamiliar with the formation elsewhere." Dr. Tarr is quite unjustified in saying we regard the Boone formation outside the Tri-State district as being free from chert, for no such statement appears in our paper, and we had no intention of conveying this impression. We have noted chert elsewhere in the Boone, and in other limestone, in many parts of the Ozark uplift and Mississippi Valley generally. We have studied excellent exposures of chert in limestone near Osceola, Sedalia, Clifton City, Columbia, Missouri and Eureka Springs and many other places in northwestern Arkansas. These occurrences appear to be similar to that of the chert in the Tri-State district, except that the deformation and chertification are much less intense. We limited our paper very largely to the Tri-State district, and so stated on the first page.

On page 466, describing the origin of chert, Dr. Tarr states:

> The chert in this formation (the Boone), as the writer has shown in the articles cited,[8,9] is primary, having been deposited with the limestone. Its distribution over thousands of square miles, the widespread occurrence of the chert in the same zone, its persistence along a given horizon within that zone, and innumerable other lines of evidence, prove its syngenetic origin.

We are fully aware of the widespread distribution of the chert and are not unmindful of the problem of accounting for its origin. But perhaps even that is not more difficult than to account for some other remarkable geological phenomena such as 200,000 square miles of lava flow of great thickness in the Columbia and Snake rivers plateau, many of the flows having been deposited in nearly horizontal beds, showing that the older underlying formations were little affected by the transfer of this great mass of material from below.

With the structural relationship of chert to limestone so obvious, we find difficulty in substituting a conception of the marine deposition of silica within the original calcareous deposit in such a manner as would account for the present concentration of the chert in the zones which were deformed at a period remote from the initial deposition of the limestone.

Vertical exposures along bluffs may sometimes appear to verify the assumption that the beds are everywhere equally chertified. But usually such bluffs are themselves expressions of structural features similar to shear zones observable underground. And, as Dr. Dake, of Rolla, Mo., pointed out in discussing our paper on the ore deposits of this district, the horizon may be quite lacking in chert a short distance in from the face of the bluff.

Regarding Dr. Tarr's criticism of the term "chertification," we found that "silicification" has so many meanings and is applicable to so many types of rocks that we felt forced to coin the term "chertification" to express the definite concept of the replacement of limestone by silicic acid to form chert.

As to Dr. Tarr's statement on page 466 that chert: " . . . beds that are 10, 20, 50, or more feet thick are known," we fully agree that there are many places where the beds of chert are locally of the thicknesses mentioned, but if Dr. Tarr would follow these same beds away from the zones of deformation he would find that they become predominantly limestone.

Dr. Tarr, further, does not reveal adequate familiarity with the chert of the Tri-State district or of the Boone formation as a whole by his statement on page 470: "The original distribution of the chert was uniform along or within a given bed in the limestone." As is repeatedly noted in this paper, the chert certainly is not now uniformly distributed along or within any given bed, and we fail to see what evidence Dr. Tarr may have that it ever was so distributed.

On pages 470 and 473, under the headings "Underground Circulation" and "Breccia Formation," Dr. Tarr submits a long discussion in which he offers no specific field data, nor information concerning the respective beds or horizons in which his underground circulation takes place, other than the following statement on page 471: "The movement of underground water was facilitated by the presence of chert lenses and nodules,

but was especially active in the Grand Falls (Boone) chert horizon. The solution channels followed this horizon chiefly, but also extended upward and downward." This statement is not supported by the field conditions we have observed.

The so-called Grand Falls chert horizon, which falls within our O, P and Q beds in the Oklahoma-Kansas field, and which is not everywhere chert, is not the chief horizon followed by solution channels and is relatively unnotable in this respect. The horizons 25 to 100 ft. above the Grand Falls, and especially M bed in our classification, furnish much better examples of solution channels and brecciation, and especially of mineralization. To date only four mines in the main Oklahoma-Kansas

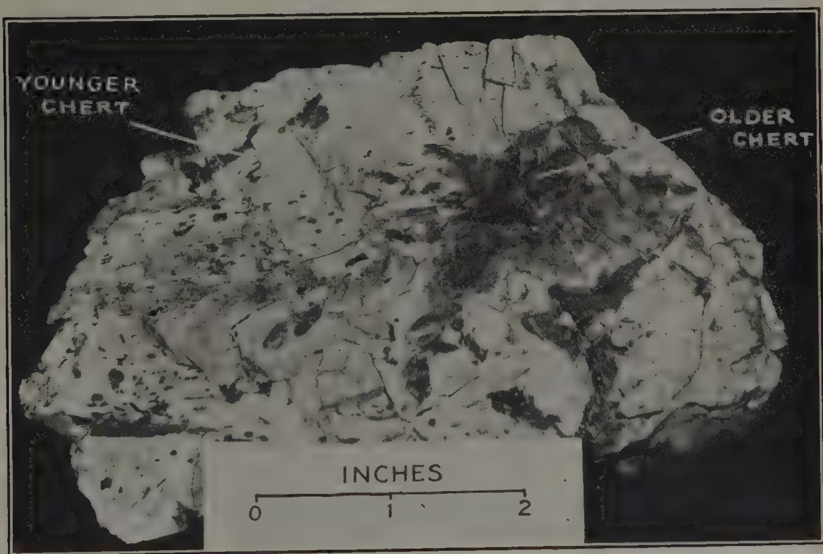

Fig. 20.—From Navy Bean mine, near Wentworth, Missouri.
Older chert (dark) and younger chert (light).

field have found commercial orebodies in the Grand Falls horizon. These mines lie within an aggregate area of 240 acres out of 25 square miles of mining territory in this particular field. The Grand Falls horizon is more important in the Baxter Springs area to the northeast of the main Oklahoma-Kansas field, where it compares favorably with the upper horizons. In the southwestern Missouri zinc-lead districts it was the most important horizon.

In his summary on page 479, Dr. Tarr reiterates his belief that "the chert of the Boone formation . . . is primary or syngenetic and was deposited chemically on the sea floor at the time of the deposition of the enclosing limestone beds" and that " . . . this view is in keeping with the *latest* theories as to the origin of chert."

Theories, of course, to be of any value must explain the facts. Obviously Dr. Tarr is not familiar with the essential facts regarding the distribution of the chert and of the orebodies in the Tri-State mining field.

Acknowledgments

We are indebted to Mr. M. D. Harbaugh of Miami, Oklahoma, for criticism and many suggestions regarding this paper.

As usual, we discussed stratigraphy with Messrs. H. A. Buehler and H. S. McQueen, of the Missouri Geological Survey, as our studies are confined very largely to the Boone in detail and theirs embraces Ozark strata in general.

We wish to thank Mr. W. S. Burbank of the U. S. Geological Survey, who spent a few days with us during the summer of 1933, for the underground pictures that help to explain better the conditions as we have observed them.

Mr. M. H. Gidel, one of our old associates at Butte, Mont., spent a number of months with us in this district in 1927 and has continued to offer valuable suggestions, some of which are incorporated in this paper.

Mine owners, operators, engineers and miners, too numerous to mention, have aided us materially in many ways.

Recent Literature on the Tri-State Mining District

1. D. C. Barton: Notes on the Mississippian Chert of the St. Louis Area. *Jnl. Geol.* (1918) **26**, 361–374.
2. G. M. Fowler: Oil and Oil Structures in Oklahoma-Kansas Zinc-Lead Mining Field. *Bull.* Amer. Assn. Petr. Geol. (1933) **17**, No. 12.
3. G. M. Fowler and J. P. Lyden: The Ore Deposits of the Tri-State District (Missouri-Kansas-Oklahoma). *Trans.* A.I.M.E. (1932) **102**, 206–251.
4. J. G. Grohskopf and C. O. Reinoehl: Magnetic Surveys. Missouri Bur. Geol. and Mines 57th *Biennial Report* (1933) Appendix IV, 1–20.
5. C. K. Leith: Silicification of Erosion Surfaces. *Econ. Geol.* (1925) **20**, 513–523. Structures of the Wisconsin and Tri-State Lead and Zinc Deposits. *Econ. Geol.* (1932) **27**, 405–418.
6. G. R. Mansfield: Geography, Geology, and Mineral Resources, Southeastern Idaho. U. S. Geol. Survey *Prof. Paper* 152 (1927) 370.
7. H. S. McQueen: Insoluble Residues as a Guide in Stratigraphic Studies. Missouri Bur. Geol. and Mines 56th *Biennial Report* (1932) Appendix I, 102–131.
8. W. A. Tarr: Origin of the Chert in the Burlington Limestone. *Amer. Jnl. Sci.* (1917) **26**, 409–452.
9. W. A. Tarr: Origin of Chert and Flint. Univ. of Missouri *Studies* (1926) **1**, No. 1.
10. W. A. Tarr: The Miami-Picher Zinc-Lead District. *Econ. Geol.* (1933) **28**, 463–479.
11. W. A. Tarr and W. H. Twenhofel: A Treatise on Sedimentation, Ed. 2. 1932.
12. S. Weidman: The Miami-Picher Zinc-Lead District, Oklahoma. Oklahoma Geol. Survey *Bull.* 56 (1932).
13. E. A. Bastin: Relations of Cherts to Stylolites at Carthage, Missouri. *Jnl. Geol.* (1933) **41**, 371–381.
14. W. H. Emmons: The Origin of the Deposits of Sulphide Ores of the Mississippi Valley. *Econ. Geol.* (1929) **24**, 221–271.

15. A. W. Giles: Boone Chert. Tulsa Geol. Soc. *Digest* (1933) 45–54.
16. W. H. Newhouse: The Temperature of Formation of the Mississippi Valley Lead-zinc Deposits. *Econ. Geol.* (1933) **28**, 744–750.

PART II

By F. E. Gregory*

It is obvious that a complete and rigorous development of the subject of chertification, even as applied to the Tri-State district, would require a prohibitive amount of field work, petrographic studies and chemical analysis. Accordingly, it has been proposed to report the work to date, giving a rather general discussion of the subject and submit papers later that will deal more concisely with specific phases of the subject.

Many erroneous conclusions have been arrived at with respect to the origin of the Tri-State cherts. Most of these conclusions were the result of either too close adherence to theories evolved in the study of other fields, or a too cursory and unmethodical an examination of the problem at hand. Such theories are but a graphic illustration of the fact that little is to be gained by the invoking of tenuous and subtle hypotheses as a vehicle for the explanation of natural phenomena.

General Discussion

Structure studies in the Tri-State district show that the chertification of the Boone limestone had its inception along zones of deformation. The silica-bearing solutions followed channels formed by regional movement and spread outward into the strata. Obeying a natural law, the path followed laterally was the one of least resistance; namely, stylolites, bed partings, and, more slowly, percolation through and along the more porous of the beds. Diffusion was generally confined to a radius around the seat of infiltration. It is to be remembered that diffusion is but the movement of molecules from fields of higher concentration to one of lower concentration. Thus it must of necessity be slow. Experiments conducted in the writer's laboratory show that the movement of silica-bearing solutions through very granular limestone can be approximately represented by the formula $R = CZ\sqrt{t}$ in which R is the rate of diffusion in millimeters per hour, C the concentration of SiO_2 in mols per liter, Z the diameter of the average calcium carbonate crystal in millimeters and t the temperature in degrees centigrade. It is recognized that the only value of such an empirical equation lies in its power to help visualize the extreme slowness of such movements. Such data are in complete accord with observed facts in the field, in that chertification has taken place principally along stylolite partings and other channelways of relatively easy ingress for the silica-bearing solutions.

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Several analyses of limestone are given in Table 3, in order to show its composition in strata where there is no megascopic evidence of chertification.

TABLE 3.—*Analyses of Limestone*

Constituent, Per Cent	From Quarry on Shoal Creek near Joplin, Mo.	From Cedar Bluff near Galena, Kansas	From Short Creek, Kansas Massive L Bed
SiO_2	1.76	1.96	2.12
Al_2O_3 and Fe_2O_3	0.57	0.89	1.09
CaO	54.49	53.88	53.66
CO_2	42.31	42.34	42.25
Total	99.13	99.07	99.12

Two distinct cherts are found in the district. The older one is of cryptocrystalline structure and is found around some centers of deformation and along some of the stylolite partings, the delineation being due, doubtless, to a greater concentration of silicic acid solutions at these points. The younger chert is found in abundance in many parts of the district.

OLDER CHERT

Structurally, the older chert is composed of ovaloid grains of chalcedony set in a matrix of quartz grains and sponge spicules. Often the spicules have been etched and rounded by solution. Pyrite, marcasite, inclusions of limestone, and a small amount of tourmaline are also present.

TABLE 4.—*Analyses of Older Chert*

Constituent, Per Cent	A	B	C	D	E
SiO_2	98.83	98.61	99.12	98.49	98.60
Al_2O_3	0.43	0.39	0.61	0.46	0.78
CaO	0.07	0.38	0.09	0.15	0.11
Fe_2O_3	None	None	None	None	0.09
FeO	0.11	0.21	0.33	0.14	None
MgO	0.05	0.18	0.11	0.06	0.03
Ignition	0.15	0.19	0.31	0.43	0.26
Total	99.64	99.96	100.57	99.73	99.87

A. Older chert from M bed, Oklahoma field.
B. Older chert from the Grand Falls, Missouri.
C. Older chert from L bed, Center Creek, Missouri.
D. Older chert from D bed, Big John mine, Picher, Oklahoma.
E. Older chert from tripoli fields, Seneca, Missouri.

Chert of this generation varies but little in composition and specific gravity from place to place in the field. Table 4 shows five analyses of this type.

This chert contains relatively few distinct fossils except sponge spicules. On thin sections, however, the shadowy outlines of crinoid stems and coral tests can be seen. Chertification has been intensive and has all but obliterated the casts of the great number of fossils that must have been present in the original limestone.

In color the older chert grades from a dark brown to a clear white. The dark color is due principally to the presence of organic matter, no doubt derived from the replaced limestone, and is discharged by weathering or by prolonged leaching with an oxidizing acid.

Younger Chert

The younger cherts are generally lighter in color than the older type. The chalcedonic ovaloids are less conspicuous and less fibrous. The structure in even the most vitreous specimens is somewhat less dense than in the older, and grades down to the cellular and porous types known as cotton rock and tripoli. The sponge spicules are present but not so abundant as in the older type. Chertified fossils are abundant, as well as calcareous types in all stages of chertification.

Table 5 shows analyses of younger cherts:

Table 5.—*Analyses of Younger Cherts*

Constituent, Per Cent	A	B	C	D	E
SiO_2	98.87	96.13	89.51	61.52	43.20
Al_2O_3	0.13	0.27	0.42	0.19	0.15
$CaCO_3$	0.09	2.08	9.31	36.60	55.05
$CaSO_4$	None	None	None	None	0.16
Fe_2O_3	None	None	None	None	0.31
FeO	0.13	0.19	0.23	0.36	None
MgO	0.12	0.36	0.19	0.06	0.18
Ignition	0.32	0.39	0.51	0.62	0.61
Total	99.66	99.42	100.17	99.35	99.66

A. Chert from M bed, Bendelari mine, Picher, Oklahoma.
B. Chert from M bed, Bendelari mine, Picher, Oklahoma.
C. Chert from L bed, Short Creek, Kansas.
D. Cotton rock, Alabama Coon mine, Galena, Kansas.
E. Cotton rock, K bed, Short Creek, Kansas.

As noted elsewhere in this paper, the younger cherts of the district grade out into limestone through increasing calcium content, and often only where cut off by well defined partings is the line of demarcation clean-cut.

Brecciated fragments of the older type of chert are a common constituent of the younger, while in some areas the residual, unreplaced fragments of limestone give a typical relict structure. Even in the apparently unaltered limestone, that incipient replacement has ensued. (See Figs. 21 and 22.)

Fig. 21.—From C bed, Big John mine. Natural size.
See page 38 for chemical analysis and explanation.

The era that witnessed the deposition of the younger type of chert was one of intense chertification, as is shown by the fact that the secondary chert has engulfed the older and spread far beyond it both laterally and vertically (Fig. 23). This has resulted in the cryptocrystalline older chert being surrounded by bands of less dense semicryptocrystalline later generation chert, which grades outward into silica-impregnated limestone and cotton rock. The silica-filled limestones are in all cases farthest

TABLE 6.—*Analysis of Specimen Shown in Fig.* 21
Cuttings

Constituent, Per Cent	1	2	3	4	5	6	7	8	9
SiO_2	6.00	42.10	55.10	29.91	11.14	43.50	45.50	79.68	74.31
Al_2O_3, Fe_2O_3	1.90	2.10	1.80	0.96	1.00	0.83	0.52	0.53	0.59
$CaCO_3$	91.47	55.87	43.20	69.58	87.10	55.04	53.44	19.73	24.66
MgO	0.39	0.13	0.21	0.28	0.32	0.12	0.13	0.09	0.08
Total	99.76	100.20	100.31	100.73	99.56	99.49	99 59	100.03	99.64

from the channels of ingress, which is in accord with the law governing the percolation of silica-bearing solution through massive limestone. Table 7 shows analyses made across such a section.

FIG. 22.—FROM C BED, BIG JOHN MINE. NATURAL SIZE. See page 39. Notice incipient silica replacement in banding.

Both carbonic and acetic acid etching of specimens from all beds containing any appreciable amount of chert show portions of the unreplaced limestone to be composed of thin alternating bands of relatively

TABLE 7.—*Analyses Made across a Section of Chert*

Constituent, Per Cent	Older Chert	Younger Chert	Younger Chert	Calcareous Cotton Rock	Calcareous Cotton Rock
SiO_2	98.86	98.70	82.21	63.80	44.51
$CaCO_3$	0.02	0.10	16.65	35.45	52.94
FeO	0.06	0.13	0.18	0.18	0.27
	98.94	98.93	99.04	99.43	97.72

soluble and insoluble calcium carbonate (Fig. 24). It has been noted that in the majority of cases the invading silicic acid solutions followed the bands of highest solubility (Fig. 22).

FIG. 23.—FROM C BED, BIG JOHN MINE. ONE-HALF NATURAL SIZE. Older chert (dark—small) in younger chert (light). Limestone is also dark.

As chertification proceeded, the bands of more insoluble calcium carbonate were dissolved and silica precipitated as a replacement material. Such horizons of banded limestone formed channels for the entrance of

the solutions and undoubtedly aided in the chertification of the more massive unbanded limestone beds.

In the writer's laboratory, while experimenting on the formation of artificial chert by the replacement of limestone, the observation was made that the invading silicic acid solutions followed the same lines as had been noted as favorable in the field. However, this work is too incomplete as yet to warrant the drawing of specific conclusions.

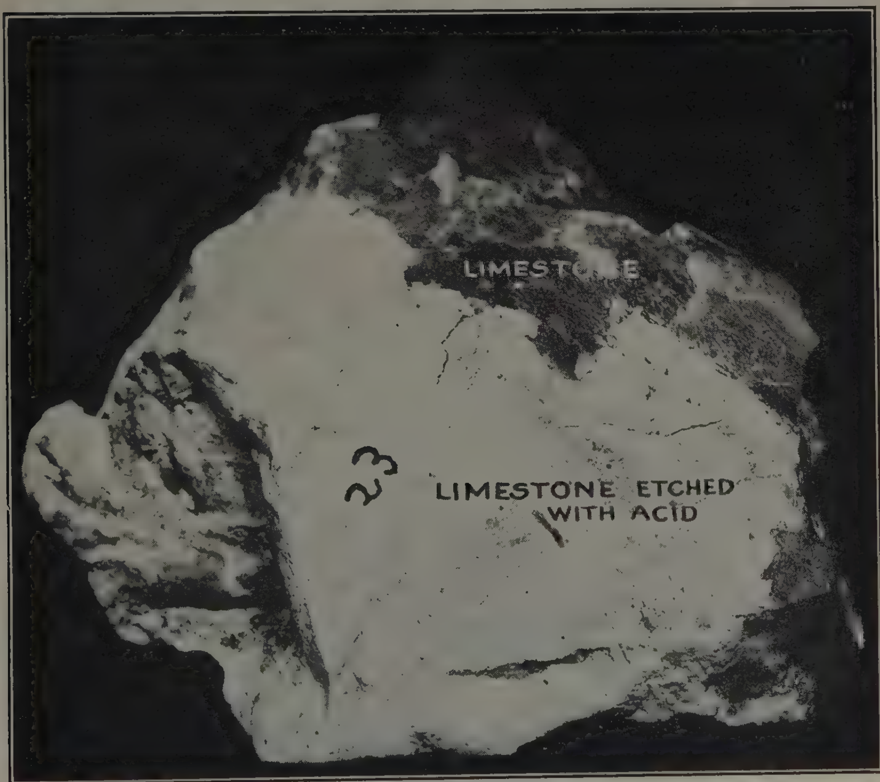

FIG. 24.—FROM D BED, BIG JOHN MINE. NATURAL SIZE.
See page 28. Limestone (dark) which has been etched with acid (light).

In the areas where chertification has been intense, the limestone along the avenues of the oldest silica deposition is completely chertified. The younger invading phase of silica deposition found the original channels obstructed and were forced to follow along the lines of contact between the virgin limestone and the older chert. This resulted in partial replacement in many cases, and in the formation of many occluded and entrapped fragments of unreplaced limestone within the chert beds (Fig. 25). Thus, away from the zones of nearly complete chertification the older type of chert disappears, and as the outer zones of younger chert are

reached the proportion of calcium carbonate to silica steadily increases. The isolated remnants of limestone within the chertified mass become

FIG. 25.—FROM D BED, BIG JOHN MINE. NATURAL SIZE. See page 141.

quite pure, indicating a dilution of solutions in the outlying regions; their irregular outline and general purity giving valuable information as to their genesis.

Tripoli

Tripoli is a common constituent of the various chertified beds throughout the district. It is closely related to cotton rock, and examples of limestone grading into cotton rock and cotton rock to tripoli can be shown. (See Fig. 26.) Thus we find all gradations between a porous chert in

Fig. 26.—From D bed, Big John mine. One and one-half times natural size. See page 42. Limestone (dark) grading to tripoli on extreme left (light).

which the calcium carbonate has been completely removed to a siliceous limestone from which little of the original calcium salt has been removed. Fig. 26 shows a gradation from low-silica content limestone through calcareous cotton rock to a highly siliceous and friable cotton rock (Table 8).

Table 8.—*Analysis of Specimen Shown in Fig.* 26

Constituent, Per Cent	A Limestone	B Calcareous Cotton Rock	C Siliceous Cotton Rock
SiO_2	7.3	40.2	89.9
$CaCO_3$	91.9	57.9	8.4
	99.2	98.1	98.3

Conclusions

Two types of cherts are shown to be present in the Tri-State district, one of older genesis than the other and each possessing distinctive characteristics. Both of them are of epigenetic origin. Certain definite relationships can be established as to their relative positions in the field.

The abundance of the silica-bearing solutions is shown by several criteria to have been greatest in the second phase of chertification.

A gradual and well defined transition from virgin limestone through siliceous limestone, calcareous cotton rock, siliceous cotton rock to highly siliceous tripoli is shown.

The fact of the gradual transitions found so abundantly, the fragments of partly and wholly unaltered limestone set in a matrix of true chert, and the partly and wholly silicified coral fossils argue strongly in favor of the replacement theory to account for the various cherts of the Tri-State district.

It is recognized that other evidence is needed to fully substantiate all the views set forth and work is being carried on along this line. However, it seems quite conclusive that the rather attenuated theory of siliceous gels being thrown down from sea water by electrolytes to become organized as cherts on the sea floor, as applied to the chert found so abundantly in the Tri-State district,[17] will have to be abandoned. All geological, mineralogical and chemical evidence so far collected combine to make such a theory no longer tenable.

PART III

By William M. Agar,* Associate Member A.I.M.E.

The descriptions and conclusions that follow are based upon the microscopic study of thin sections made from specimens furnished by George M. Fowler. Some of them are from the illustrative set of rocks and ores from the Tri-State district that was on exhibition in the Engineering Societies Building during the meeting in February, 1933; others are from specimens of chert and limestone sent to the writer more recently. The conclusions are limited to those justified by the microscopic study alone. No attempt is made here to consider the distribution of the types of chert or their relation to structure, or the other regional features of major importance that are ably discussed in the main part of this paper.

The writer wishes to emphasize the fact that much more material must be studied before all the characters and variations of the chert can be determined, but enough has been accomplished to show that the petrologic study reinforces certain of the fundamental conclusions arrived at separately by the other authors of this paper. The main results of this study can be stated as follows:

1. There are two types and ages of chert (as distinct from the jasperoid). The younger chert is more widespread in the Tri-State district than the older.

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[17] W. A. Tarr: Reference 8.

* Assistant Professor of Geology, Columbia University, New York, N. Y.

2. The younger chert was formed at some period subsequent to the formation of the limestone which it has replaced. It also surrounds and cements fragments of the older chert.

Conclusion 1.—This is not the first time that two types of chert have been recognized in this district. In 1917, F. B. Laney[18] stated that in point of age and conditions of deposition there were *three* types of chert. His *third* type, however, was the jasperoid, a formation totally distinct from the chert and not considered in this paper. His types of chert were:

(*a*) Light gray, probably contemporaneous with the limestone.

(*b*) Younger, secondary chert similar in color and texture but occurring as a replacement of limestone and in fractures in the original chert.

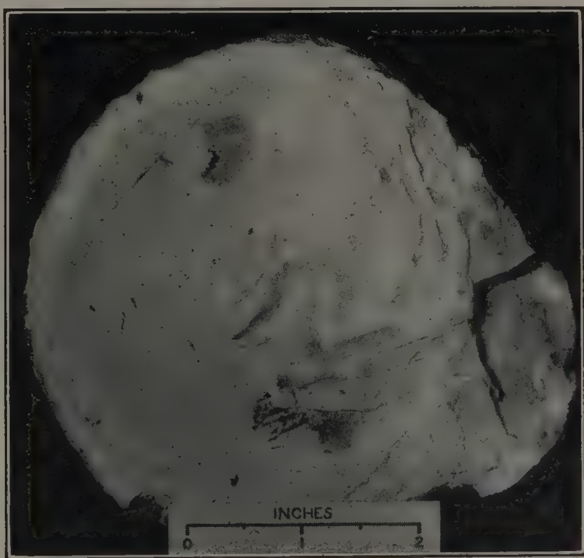

FIG. 27.—FROM TRIPOLI DEPOSIT ABOUT 1½ MILES NORTHWEST OF SENECA, MISSOURI. Chert nodule showing transition to tripoli.

Other writers[19] have also noted more than one type of chert, but no consistent attempt has previously been made to distinguish them or to determine their relative abundance.

The two types may be distinguished as follows:

(*a*) Older chert, composed of minute individual, or linked globular masses of brownish chalcedony with a microfibrous structure set in a mosaic of quartz grains that vary from 0.03 mm. in diameter down to sizes barely perceptible under high magnification. It contains many sponge spicules, visible as lenticules, cross-sections, or rare trident-shaped

[18] U. S. Bur. Mines *Bull.* 132 (1917) 99–108.

[19] E. R. Buckley and H. A. Buehler: The Geology of the Granby Area. Missouri Bur. Geol. and Mines (1906) **4**, 37–38.

S. Weidman: Reference 12.

outlines in the chert. These are composed of somewhat coarser quartz grains than the surrounding chert. Many have irregular, spiny borders; some are embayed and partly replaced by chalcedonic silica. Silicified remains of calcareous organisms are not common in this chert but they are occasionally present in considerable quantity.

(*b*) Younger chert varies from clear and colorless to brown, but without the well developed globular structure of type *a*. It is composed of cryptocrystalline silica (mostly quartz) and microfibrous chalcedony. It contains rare sponge spicules, similar to those in type *a*, and a very variable but usually large content of originally calcareous organisms in all stages of silicification. The common types are crinoid stems and arm

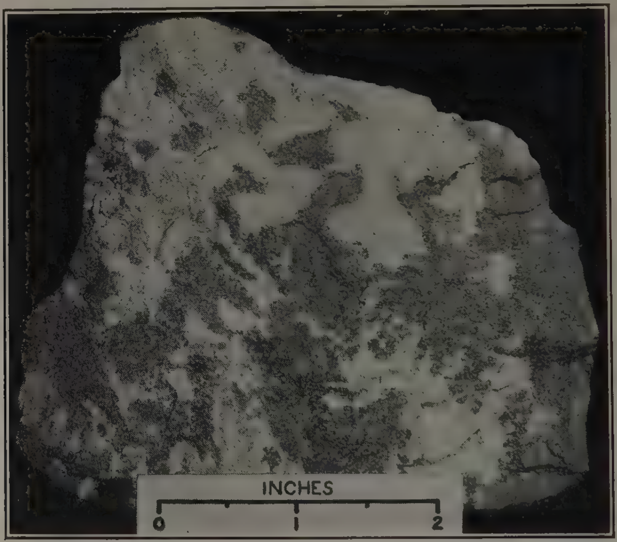

FIG. 28.—FROM D BED, BIG JOHN MINE.
Showing irregular replacement of limestone by chert (light).

plates, fragments of brachiopods and bryozoa, foraminifera, and some corals. There are all gradations between pure chert and pure limestone. The boundary between the two is never sharp.

Fig. 29 illustrates the distinction between the two types. The younger, light colored chert is not fossiliferous in this particular thin section. The older, darker chert holds many sponge spicules and occurs as irregular fragments in the younger chert. The boundaries between the two are distinct but the younger chert has reacted to some extent with the pre-existing fragments, so that the boundaries are not sharp. A thin section cut from specimen Fig. 15*a*-5 also shows angular fragments of brownish, spicule-bearing chert surrounded by clear, younger chert. In this case the older chert holds many completely silicified remains of calcareous organisms.

The two types are not always as distinct as in these cases. They often appear to merge without definite boundaries. Both varieties contain black grains and specks of which some are pyrite but most are

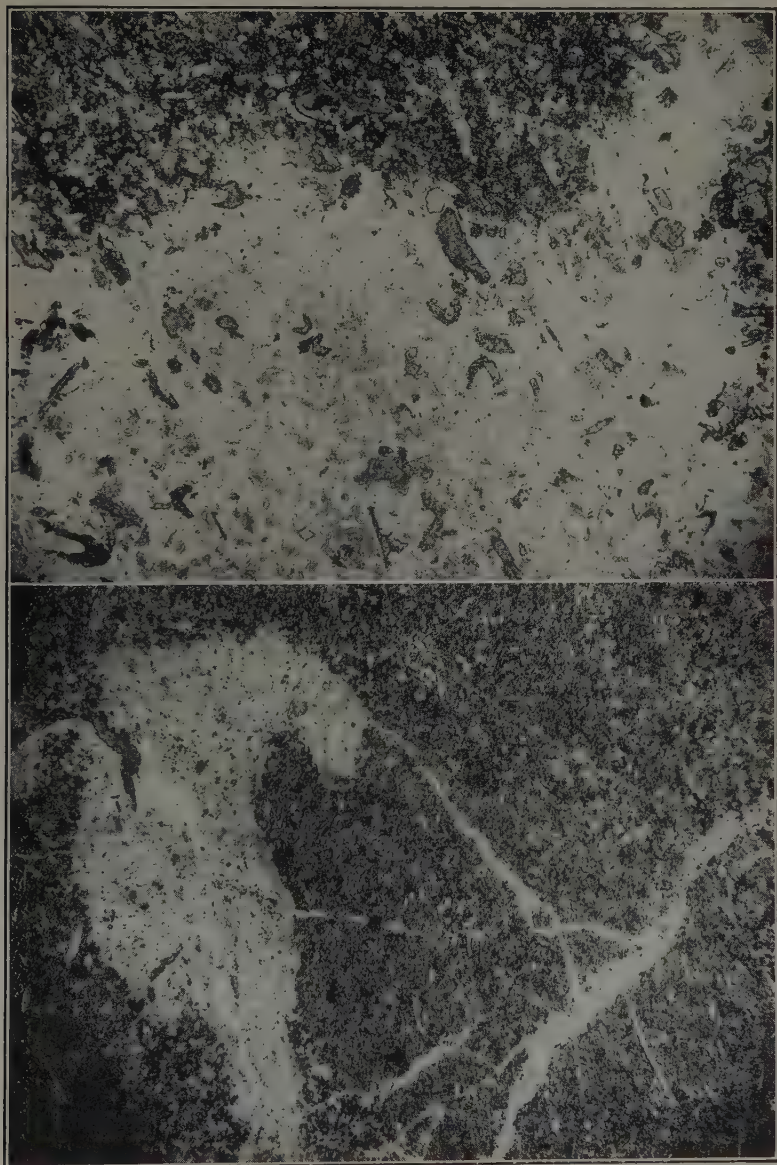

FIG. 29.—FROM H BED, EARLY BIRD MINE. FIG. 30.—FROM D BED, BIG JOHN MINE. Older chert (dark) in lighter colored younger chert. Shows irregular replacement of limestone (dark) by chert. PLAIN LIGHT, × 25.

organic matter. The aggregation of these specks into definite areas causes much of the mottling characteristic of the chert, though the intimate mingling of the two types of chert is also partly responsible for this phenomenon.

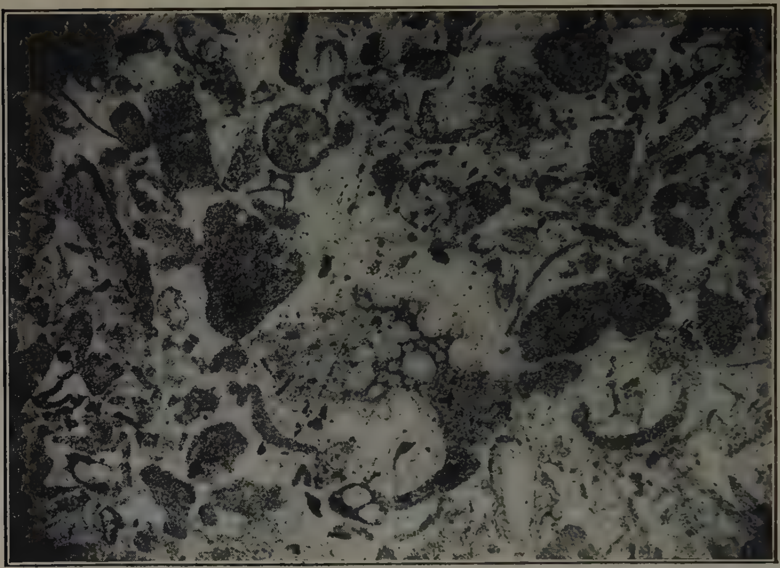

FIG. 31.—FROM M BED, BENDELARI MINE PLAIN LIGHT, × 25.
Thin section from specimen of Fig. 15a-6. Shows complete replacement of limestone and calcareous organisms by chert.

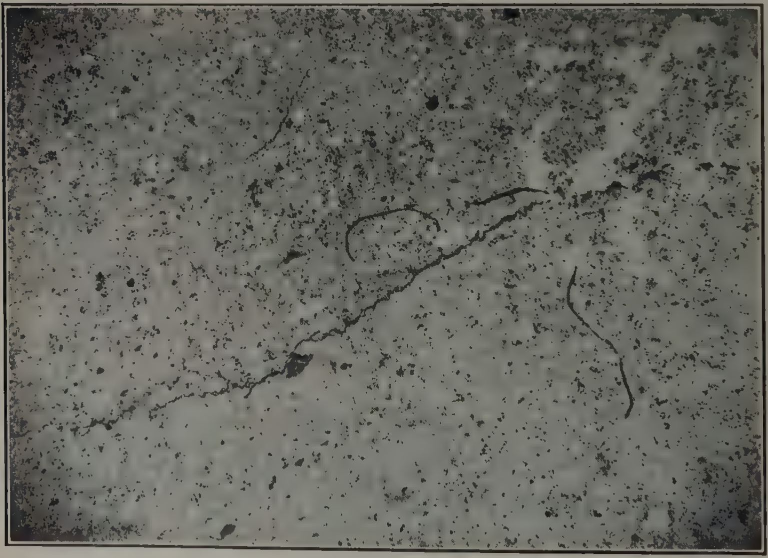

FIG. 32.—FROM F BED, GOODWIN MINE. PLAIN LIGHT, × 25.
Shows tripoli with stylolite preserved in silica.

The brown color of the minutely grained and fibrous chert is due to infinitesimal specks of brownish-black organic matter. Wherever quartz has formed in easily distinguishable grains, the disseminated brown specks are gone and the chert is clear. Glauconite and extremely rare tourmaline grains are present in the cherts. Both of these, however, and especially the glauconite, are much more common in the jasperoid.

The age relation of the older chert to the limestone is unknown to the writer. It was apparently formed and brecciated, however, before the introduction of the younger chert.

Conclusion 2.—The features that indicate replacement of the limestone by the younger chert are the following:

(*a*) Chertification of calcareous organisms. All stages of this process are evident. Calcite grains are first replaced, then chert penetrates the fossil fragments and replaces them irregularly. At a late stage of this process only a few grains of calcite remain dotted throughout the silicified fossils. Finally the former existence of calcareous fossils can be told only from the outlines that remain.

Fig. 28 is a photograph of a specimen from D bed in the Big John mine, which shows the irregular replacement of limestone by chert. Fig. 30 is a photomicrograph of a thin section cut from this specimen. It shows a typical chert-limestone boundary with ragged remnants of calcite and a few unreplaced calcareous fossils isolated in the chert which has penetrated the limestone in a very irregular fashion.

Fig. 31 is a photomicrograph of a thin section of specimen shown in Fig. 15*a*-6 from M bed in the Bendelari mine. It shows the completion of the replacement indicated in Fig. 30. The calcareous organisms as well as the calcite grains are completely replaced by chert.

(*b*) The lack of sharp boundaries between the limestone and the chert. The chert always penetrates the limestone irregularly. Pure chert gives way gradually to purer and purer limestone. This may be seen in thin sections (see description of Figs. 30 and 31 above). A thin section of the specimen shown in Fig. 15*a*-3 from M bed, Bendelari mine shows the change from pure chert with chertified fossils to incomplete replacement with remnants of calcite grains and partly chertified calcareous fossils within the space of one inch. Many others show the same features.

Hand specimens of chert nodules illustrate this feature also. A core of solid chert is surrounded by cotton rock, which is mixed chert and limestone, and this by limestone with scattered areas of chert.

Fig. 32 shows a thin section of porous tripoli from F bed in the Goodwin mine. The remains of stylolites can be seen in the siliceous rock. Other thin sections of the immediately adjacent cotton rock indicate that the tripoli differs from it only in that the calcite has been dissolved out so as to leave a relatively porous siliceous mass behind. The presence of

stylolites preserved in the tripoli is considered a proof that it was formed by replacement of a stylolitic limestone.

It is difficult to see how the features described above could be developed by any other means than replacement by relatively tenuous siliceous solutions. W. A. Tarr[20] explains the presence of fossils in the chert as the result of their falling into the soft silica gel, becoming entombed and partly silicified. He also interprets others of the features described here as the normal result of alternating formation of chert, as a silica gel precipitated on the ocean bottom, and limestone. In the writer's experience the completely silicified calcareous fossils and limestone are mostly found in the center of nodules or bands of chert, and there is a gradual transition from this into pure limestone with calcareous fossils. Such complete silicification required the removal of $CaCO_3$ as well as the introduction of silica.

This is not an argument against the formation of the chert as a gel. Silica present as the disperse phase of an emulsoid can penetrate into capillary and subcapillary openings. Cox, Dean, and Gottschalk,[21] have shown that when such a solution contains CO_2 and comes in contact with limestone, a readily ionized acid carbonate is formed, and the positively charged calcium ions precipitate a silica gel. This gel will occupy the space vacated by the dissolved or decomposed limestone and will preserve the most delicate structures. Lindgren[22] states that "Retention of structure is apparently characteristic of this type of replacement."

The fibrous structures and the cryptocrystalline aggregates in the chert indicate its origin by crystallization of a gel. The boundaries between the chert and the limestone are not as sharp as might be expected from such an origin, but instances where chertification is preceded by the formation of discrete quartz crystals are very rare, and these are believed to be connected with the introduction of the jasperoid rather than the chert.

It is, however, an argument for replacement as opposed to incorporation of fossils in a silica gel that had already set. W. H. Emmons[23] opposes the idea that isolated fragments in veins may be held up in a gel on the grounds that before the gel set they would sink, and after it had set they would not penetrate it. The same objection applies here. Furthermore, if any fossils could sink into the gel they should collect at its base. Then, in order that they be silicified, silica would have to diffuse through the silica gel.

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[20] W. A. Tarr: Reference 8.

[21] Studies on the Origin of Missouri Chert and Zinc Ores. Univ. of Missouri School of Mines *Bull.* 3 (1916) 9.

[22] Gel Replacement. A New Aspect of Metasomatism, *Proc.* Nat. Acad. Sci. (1925) **11,** 7.

[23] The State and Density of Solutions Depositing Metalliferous Veins. *Trans.* A.I.M.E. (1928) **76,** 308.

The two ages of chert also indicate a more complicated history than that pictured by the advocates of a syngenetic origin for the chert. The older chert was formed—and limestone either preceded it or was formed during the same general period—and broken apart before the younger chert cemented its fragments together. The conclusion seems inevitable that the younger chert is epigenetic and that it replaced the limestone.

DISCUSSION

(Alan M. Bateman presiding)

C. J. Roy,* Cambridge, Mass.—For the past two seasons I have been engaged in a study of the chert and jasperoid of the Tri-State district. Mr. Fowler and Mr. Lyden have been kind enough to discuss their views with me, and on many points we are in essential agreement.

The nodular chert, so characteristic of the Boone (Burlington) limestone from Iowa to Arkansas, I believe represents a segregation of silica which was precipitated with the limestone. This segregation occurred shortly after deposition, perhaps during or even before consolidation. This view, I believe, is more consistent with the facts than the hydrothermal origin proposed by Fowler and Lyden.

The so-called massive chert, which is so abundant in the Tri-State area, replaces the limestone. The massive chert surrounds the nodular variety and is therefore younger. This material ranges in color from white to dark gray and is microscopically different from the nodular chert both in average grain size and in composition. This material, I now believe, represents the initial silicification by hydrothermal solutions.

During the formation of the massive chert much limestone was dissolved, allowing the nodular chert and the massive chert already formed to slump and form the breccias. I think the mode of occurrence of the breccias and the fracture systems in the mines are better explained by this mechanism than by that proposed by Fowler and Lyden.

In the later stages of the hydrothermal silicification sulfides were brought in and the ores and the black jasperoid were formed. The presence of sericite in the jasperoid, especially where the latter replaced shales, seems to indicate a hydrothermal origin for this material. I have found sericite also in some of the material here called massive chert. Tourmaline has been described by Weidman as occurring in the jasperoid. I have found a few grains which are similar to detrital tourmaline found in sedimentary rocks elsewhere in Missouri.

G. M. Fowler and J. P. Lyden (written discussion).—It is our observation in the field that nodular and massive chert differ only in the manner of infiltration of the silicic acid solutions. Either of them may be of the *older* or *younger* variety and both replace limestone.

The fracture systems and breccia, so common in the Tri-State district, are definitely related to structural deformation. Solution of strata was secondary and of minor importance in forming them. Evidently Mr. Roy has not given much attention to these phenomena.

R. H. Sales,† Butte, Mont.—I assume that Dr. Agar's study of the chert is laying the foundation for future investigations of the ore deposits in this district. I see no immediate connection between the matters treated in his paper and the ore occurrences. The reasons for Dr. Agar's efforts to distinguish two ages of chert are not

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clear. While Fowler and Lyden stress their claim that the chert is not syngenetic, but was introduced, Dr. Agar fails to supply any evidence as to how the silica of the older chert was introduced or where it came from. It would be interesting to know whether Agar's work with the microscope supported the position of Fowler and Lyden, or whether it tended to show a syngenetic origin.

W. M. Agar (written discussion).—Mr. Sales' assumption that the study of the chert was preliminary to a more extended study of the ore deposits of the region is correct. It was undertaken at Mr. Fowler's request, to determine, if possible, whether the great masses of chert in the Tri-State district are primary or introduced. The evidence cited in favor of an epigenetic origin for the younger chert appears to be decisive, and it is hard to understand the import of Mr. Sales' last sentence. No evidence that indicated the origin of the older chert was found and so no origin was ascribed to it. The fact is that I saw little of it, but what I did see, without conscious effort, convinced me that there were some fragments of chert cemented by another type of chert. This was an observation and was therefore recorded. It does not simplify the relationships or uphold any particular theory. The fact remains that much the greater part of the chert is clearly epigenetic and replaces the limestone.

Mr. Sales sees no immediate connection between this study and the ore occurrences. This is not the place to elaborate on that question, but I have just spent a week in the area under discussion, and a study that began as a laboratory investigation of the relationship of chert to limestone now appears to me to have a much broader significance.

G. M. Fowler and J. P. Lyden (written discussion).—Our interest centers in the great quantities of introduced chert so common throughout this district. In the field we are seldom able to distinguish the *older* from the *younger* variety.

There is a very close structural relationship between the chert, early dolomite, and ore. Each of these deposited, in the order stated, in the same general zones of structural deformation and successively recemented these zones after each of the three important periods of deformation. In the Oklahoma-Kansas field practically all of the ore is confined to the zones of structural deformation and is found replacing the early dolomite and filling openings of various sizes in the brecciated and deformed chert. Unaltered limestone is nearly always barren.

It is unnecessary to describe post-ore deformation and mineralization at this time.

S. St. Clair,* New York, N. Y.—Some 20 years ago, when connected with the Missouri Bureau of Geology and Mines, it was my privilege to work several years in the Ozark Mountain region. In no other area that has come under my observation is there an amount of chert comparable to that in the Ozarks. The chert extends stratigraphically from the Cambro-Ordovician to the Chester of the Mississippian.

In my work, the question arose as to whether the chert was primary or secondary. My conclusion was, that, as found today, the chert is, in most part, a secondary replacement of the dolomites, but it was my conclusion also that much, if not most, of the silica was deposited syngenetically with the limestones and dolomites, the concentration into nodules, masses, and even whole beds of considerable outcrop being the result of circulating meteoric waters. For example, I collected any number of samples of what I came to recognize as siliceous dolomite and when these were boiled intensively in hydrochloric acid there would be left from 25 to 75 per cent of silica. It would appear reasonable to believe that, owing to the high concentration of silica in the water, some of the more extensive beds of chert may be primary, originally being deposited on the ocean floor as a silica ooze. For the source of all this silica over such a long period of geologic time, I shall advance no theory.

* Consulting Geologist.

Fowler and Lyden have used the word "chertification" for the Tri-State area. This term may be well chosen. However, for the Ozark region as a whole and the chert therein, I prefer the term "silication," to cover the replacement of the limestone and dolomite by the silica. In general, this silication has taken place irrespective of structural condition and water channelway thus provided. I failed to note any increased silication along faults and fissures in Southeast Missouri and in the Central Ozark region. This would indicate that the primary silication had taken place prior to the faulting and fissuring. To some extent, secondary silication has taken place and is probably continuing even today.

This statement may in no way conflict with the deductions of Fowler and Lyden, whose studies of the Boone formation in association with the zinc ores of the Tri-State district show the chertification to be induced by silica-bearing waters of two ages. I am speaking in general of the silication of rock formations that extend from the Cambro-Ordovician to the Mississippian. The larger aspect should not be overlooked by Fowler and Lyden, and, conversely, Dr. Tarr should probably not apply his general syngenetic theory, with which I am largely in sympathy, to an ore-bearing area in which there were, without doubt, special depositional and metamorphic conditions.

G. M. Fowler and J. P. Lyden (written discussion).—It is our understanding that the term "silication" already has another meaning, which prohibits its use in the way that Mr. St. Clair suggests.

A. O. Hayes,* New Brunswick, N. J.—I have observed that there is a good deal of secondary silica, deposited subsequent to the formation of the ores in the Wabana iron deposits. Apparently the oxidation and leaching of the alumina and the iron silicates provided the secondary silica. So, in argillaceous deposits one may quite conceivably have secondary silica derived from the alumina of the clay.

W. F. Pond,† Nashville, Tenn.—From my own observations I can agree with the thesis that the chert is later than the limestone, in the main, although some of it may be primary. One of the speakers mentioned nodules formed on the sea bottom with the clay sediments slumped around them. In the marble quarries at Phoenix, Missouri, probably at about the M beds, I have seen some nodules, up to 12 in. across, with what are apparently shrinkage cracks in the surface. These cracks are ⅛ to ¼ in. wide at the nodule's surface and pinch out towards the center. They also pinch out laterally along the surface. These might easily be nodules formed on the ocean floor, developing shrinkage cracks, into which the limestone ooze penetrated.

G. F. Loughlin,‡ Washington, D. C.—There is a general similarity between the chert-jasperoid problem in the Tri-State region and in several of the western mining districts. The wide difference in age between chert nodules and lenses on the one hand and masses of jasperoid on the other is expressed in some places (for example, Tres Hermanas, N. Mex.) by the reaction rims of contact-metamorphic minerals around chert nodules, which therefore antedated the entire period of mineralization, whereas deposition of jasperoid took place only during stages that followed contact metamorphism. Large masses of jasperoid are found not only near the contacts of intrusive stocks but miles away from them, and it is common, in any occurrence, to find the main mass of jasperoid shattered and recemented by a later stage of jasperoid, which in turn commonly precedes the principal stage of sulfide deposition.

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‡ Geologist in Charge, Section of Metalliferous Deposits, U. S. Geological Survey.

A. W. GILES,* Fayetteville, Ark. (written discussion).—During the past three years the writer has been investigating the character and features of the Boone chert. The study is now completed and the results obtained during the progress of the investigation have been presented at various times.[24] The conclusions resulting from the investigation are in essential agreement with the conclusions reached by Fowler, Lyden, Gregory and Agar. The studies of the Boone by Fowler and his colleagues were confined chiefly to the Tri-State mining district, a highly mineralized area. The investigation made by the writer embraced an area of approximately 3500 square miles in northeastern Oklahoma and northwestern Arkansas, a region of insignificant mineralization from the standpoint of ore deposition. Possibly the most interesting and significant result of the two sets of studies made independently in different areas of unlike mineralization is the revelation of the persistence and similarity in the features of Boone chert which have resulted in similar conclusions.

In the area investigated by the writer the Boone is about 300 ft. thick and consists of limestone largely but very irregularly and incompletely crystallized. Two types of "chert" were recognized, insoluble (vitreous) and partly soluble ("cotton rock"). The partly soluble type represents limestone in various stages of silicification, and quantitatively is as important as the insoluble type. The two types may gradually or irregularly grade into each other, suggesting contemporaneity in origin. Either type may occur as ramifications, knots, nodules, lenses and sheets irregularly distributed through the limestone, and as distinct beds.

Analysis of the measurements of nearly 100 widely separated sections of the Boone limestone in Oklahoma and Arkansas indicate the relative proportion of limestone to chert to be 42 to 58, more than half of the Boone consisting of chert. Using this proportion as a basis the total amount of chert in the Boone outcrop of Arkansas and Oklahoma was found to be 156 cubic miles. The tabulated results of the measurements indicate an irregular but progressive decrease eastward from Oklahoma to Harrison, Ark., in the degree of chertification of the Boone limestone. The results of the measurements indicate also that the lower half of the Boone has 15 per cent more chert than the upper half, and the lower third 11 per cent more chert than the middle third, and the middle third 10 per cent more chert than the upper third of the limestone.

Examination of a large number of logs of wells drilled in Arkansas, Oklahoma and Kansas indicate as extensive chertification of the Boone beneath thick cover as in its surface expression. The age of the bulk of chertification is assigned to the pre-Chester since the basal Chester resting upon the Boone contains nearly everywhere a conglomerate consisting largely of Boone chert and limestone pebbles, and since the chert persists throughout the known extent of the Boone beneath a thick cover of Chester and Pennsylvanian formations.

Detailed studies of the structural, stratigraphic, paleontologic, chemical and microscopic features of the Boone chert unmistakably indicate that essentially all of the chert was deposited as replacement subsequent to the deposition and consolidation of the Boone limestone. Features described and illustrated by Fowler and his co-authors in their study and described and illustrated by Bastin[25] are normal

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[24] A summary of the results of a part of the investigation was incorporated in an address on the stratigraphy of northern Arkansas to the members of the Kansas Geological Society annual field conference, Sept. 5, 1933, at Harrison, Ark. The results were presented more fully to the Tulsa Geological Society, Nov. 20, 1933, and published in abstract in the Tulsa Geological Society *Digest* (1933) 45–54.

[25] Reference 13.

and characteristic of Boone chert and may be found in nearly every recent exposure of the Boone in Arkansas, Oklahoma, and Missouri.

The writer has also made an intensive and exhaustive study of the possible origin of the siliceous solutions that formed the chert. Any theory attempting to explain the origin of Boone chert must satisfactorily account for the vast quantity of chert relative to the total thickness of the limestone, the irregular areal and stratigraphic distribution of the chert, the preponderance of chert in the lower part of the formation, the variation in solubility of the greater part of the chert, the overwhelming evidence of replacement of the limestone by the chert, and the pre-Chester age of the greater part of the chert.

Investigation of the possibility of derivation of the silica from within the Boone limestone yielded negative results, the chief objection resting upon the high degree of purity of the limestone. Nearly 100 analyses, gathered from many sources and many made in the mineralogy laboratory of the University of Arkansas, indicate an average silica content of less than 1 per cent for the average sample of Boone limestone free from chert.

The possibility of derivation of the silica from above the limestone either from overlying siliceous formations or from a post-Boone pre-Chester erosion surface was found untenable. Likewise the maximum quantity of silica that possibly might have been precipitated from rising meteoric solutions is regarded as wholly incomparable to the quantity of chert present in the Boone limestone.

Attempted application of the concept of hydrothermal origin of the chert from a deep-seated magmatic source was found to have both favorable and unfavorable factors. The favorable factors include evidence of widespread magmatic conditions in the Mississippi Valley region, chiefly as dikes, ores and fluorite, including the widespread ores of hydrothermal origin in the Boone; they postulate a source adequate to supply the vast amount of silica present in the Boone; and they explain the decrease upward in chertification of the limestone, and greatest chertification in the most disturbed areas (Oklahoma), decreasing eastward in Arkansas. Difficulties encountered in the application of the theory of hydrothermal origin reside in the mechanics of ascent of hot solutions through a stratigraphic column 1800 ft. or more thick, with little faulting as in northwest Arkansas, absence of comparable chertification of the basal St. Joe member of the Boone, and underlying formations and, most serious of all objections, the widespread distribution of chert in Mississippian limestones of North America, Europe and Asia. A phenomenon so widespread should rest upon a common cause; hence if the Boone chert is hydrothermal in origin presumably extensive and widespread Mississippian chertification elsewhere should likewise be hydrothermal, which would demand vulcanism of middle or later Paleozoic essentially coextensive with the distribution of Mississippian chert, a postulate not demonstrated as true.

The possible syngenetic origin of the chert, either contemporaneous or penecontemporaneous with the enclosing limestone, was found to possess so many difficulties that no appreciable part of the chert is regarded as syngenetic in origin. The chief difficulty resides in the manifold evidence of replacement of consolidated limestone by the chert. Other difficulties are the absence of chertification of the underlying St. Joe limestone, the irregular vertical and areal distribution of the chert, the partial and complete silicification of fossil remains, the freedom of the chert from sea floor sediment, the variable composition of the chert, the gradation of chert through silicified limestone into limestone free from chert, the vast quantity of chert representing various degrees of silicifications of limestone: and finally the syngenetic hypothesis fails utterly and absolutely to explain the textural and structural features of the chert, such as relics of bedding, areas of coarsely crystalline calcite within chert lenses and

nodules, relationship of chert to stylolites and chert nodules to bedding planes, and other features prevalent in every exposure of the Boone limestone.

G. M. Fowler, J. P. Lyden, F. E. Gregory and W. M. Agar (written discussion). Dr. Giles' discussion emphasizes many features outside the scope of our study and points out the original purity of the Boone limestone.

W. S. T. Smith, Palo Alto, Calif.—I have not heretofore ventured to express an opinion as to the origin of the cherts of the Joplin region, because of the uncertain or conflicting character of much of the evidence, and because I have made no special study of the problem. I have, however, studied these cherts in considerable detail, both in the field and in thin section under the microscope, and certain considerations seem to me clear enough to be put forward at this time.

Three different general hypotheses of origin have been offered: (1) that they are original chemical precipitates, syngenetic with the limestones with which they are associated; (2) that they are primarily original deposits of siliceous organic remains, modified by recrystallization; and (3) that they are replacements of limestone. I incline to the view that the cherts are, as a whole, the result of the crystallization of deposits composed largely of the remains of organisms having siliceous skeletons or tests; that there has also been some replacement of limestone, but that this is of minor importance.

The hypothesis of chemical precipitation appears to me untenable. The widespread distribution of cherts in the pre-Pennsylvanian limestones and dolomites of the Mississippi Valley; their erratic distribution at any given horizon, and their unlike distribution at different horizons; their frequent occurrence in nodules and short lenses, and their constant association with calcareous rocks, rather than an indiscriminate association with limestone, sandstone and shale, all suggest an origin from siliceous organisms, rather than from chemical precipitates, whether directly from the sea itself or from siliceous springs emerging on the floor of the sea.

The widespread, erratic distribution of the chert appears to me to be also opposed to the replacement hypothesis, since known replacements are neither so widespread nor so irregularly and apparently unaccountably distributed. Replacements are ordinarily the result of special local conditions. There is, too, the difficulty of accounting for the large amount of silica required for such extensive replacements, and for the carbon dioxide essential to the solution of the replaced limestone, since most of the solution must have taken place far below ground-water level. The extensive occurrence of jasperoid replacing limestone, in the orebodies of the Joplin region, when compared with the small amount of silica carried in solution in the underground waters of this area, suggests that very small amounts of silica in solution may result in widespread replacement if sufficient time is given. The presence of silica in the underground waters, however, is not the only factor involved. For, although limestones are much the most abundant rocks of the Ozark region and occur at all horizons from Mississippian to Cambrian, and although silica in small amount is present in all the underground waters of the region, the replacement of limestone by jasperoid is known from only two areas, the Joplin region and northern Arkansas, which together form but a small fraction of the Ozark region as a whole. In the Joplin area the jasperoid is found only in the upper half of the Boone formation, and appears to occur here only where the limestone it replaces was previously deformed by slight shearing or flowage. The replacement by jasperoid thus involves only a very small part of even the Joplin area. Moreover, the volume of the jasperoid, though large, is insignificant when compared with that of the cherts of this area alone. This occurrence of jasperoid serves to illustrate the point suggested above, that extensive metasomatism is not associated with normal widespread underground

conditions, but is the result of abnormal and usually local conditions. Rocks are generally stable as long as they remain under essentially stable conditions, and metasomatism is commonly due to some change in the environment.

The rocks of the Joplin region lack some of the features commonly met in replacement deposits. As seen in the field they are, as a rule, definitely either chert or limestone, the one, ordinarily, when fresh being sharply separated from the other. Only occasionally are rocks of intermediate character found. If the cherts were primarily replacements, partially replaced limestone and limestone grading into chert should be much more common than they are. In the jasperoid replacements of limestone, in the orebodies of the Tri-State district, are many occurrences of transitional rocks.

Massive replacements commonly mimic, in greater or less degree, the rocks that are replaced. I have seen fluorite replacing sandstone, smithsonite replacing limestone and chert, and cerussite replacing weathered chert; all, when viewed from a short distance, scarcely to be distinguished from the unreplaced rock. Even jasperoid, if it were a light instead of a very dark gray, would not be unsuggestive of the limestone that it replaces. Chert, however, is wholly unlike the limestone with which it is associated.

Then, too, the grain of a replacement, although often somewhat finer than that of the original rock, commonly varies with variations in the grain of the latter. At the Old Jim mine, in western Kentucky, smithsonite occurred replacing both limestone and the associated chert. When replacing limestone it had both a color and grain approaching that of the rock replaced, the grain in the different replaced beds varying with the variations of the grain of the limestone. On the other hand, when replacing chert it was nearly white and had an extremely fine grain, much like that of the chert. In one slide examined the grain varied but slightly, the average diameter of the grain being about 0.0035 mm.; whereas a thin section of replaced limestone showed an average diameter of grain of about 0.07 mm., or 20 times the first-mentioned average.

When a laminated limestone of the Joplin region is replaced by jasperoid, the different laminae of the limestone varying slightly in grain, the replacement varies in grain in a similar manner, and is in consequence faintly banded. While banded jasperoid is common in the Joplin region, nothing similar to these variations has been noted in the cherts.

It would seem to follow, therefore, that when a rock as coarse grained as limestone is replaced by silica the replacement would be relatively coarse grained, not as fine grained as chert. Where limestone is known without question to be thus replaced, the replacement is almost without exception jasperoid, which is much coarser grained than chert; being, in fact, a quartzite, with quite different characteristics from chert.

Even the mode of occurrence of chert suggests original rather than secondary deposition. Limestone does not occur normally in small nodules enclosed within limestone, whereas this is one of the characteristic modes of occurrence of chert.

Any facts bearing on the age of the chert may help to throw light on its origin. Fowler and Lyden apparently believe that the cherts were formed after the deformation of the region. Even if there were no other evidence, this view is opposed by the inclusion of angular fragments of chert in the jasperoid of the orebodies, which is so characteristic of the breccias of this region. For there is abundant evidence to show that these angular fragments of chert were included in the limestone prior to its replacement, as a result of the flowage of the limestone about them, this flowage having been caused by the compressive stresses accompanying the deformation of the region. Moreover, the structural features of many of the mines in the vicinity of Joplin—structures which, thus far, have never been described—show unmistakably that the cherts antedate these features.

On page 112, Fowler and Lyden say, "Our observations show that all of the chertification in the Tri-State district has a definite relationship to the structural deformation of the strata in which it occurs." And on page 129, "Our intensive study, together with our scattered observations elsewhere in the Mississippi Valley, where chert is common, leave us no choice but the conclusion that the chertification was localized by structural conditions that provided channelways for the movement of waters charged with silicic acid from some abundant source." These and other similar statements made by them would seem to indicate that they believe the "chertification" to have been the direct result of the deformation of the region; and that, because of this relationship, cherts are most abundant where the deformation has been greatest.

With respect to the association of abundant chert with deformed rocks, I am in full accord with the authors; but as to which is cause and which effect, it seems to me that they have put the cart before the horse. The localization of the deformation of the region I would explain, not as the reason for the local development of chert, but rather as the result of the local abundance of chert which clearly existed prior to the deformation.

There is evidence that the cherts are not only older than the deformation of the region, but older than the stylolites of the limestone. The age of the stylolites is not known, but they must in part at least antedate the period of deformation, since broken sections of stylolites are found occasionally in the jasperoid of the orebodies. In one excellent exposure, east of Joplin, I observed that stylolites that were normal in character along the plane between two limestone beds became greatly reduced in size when passing nodules lying in the bedding plane. Moreover, they ceased to follow their previous course, which would have cut across the nodule, and instead, followed the limestone-chert contact, along either the upper or lower surface of the nodule, or occasionally along both. These occurrences indicate that the chert must have been already present at the time the stylolites were developed.

Although fossil forms appear to be lacking in some of the cherts, they are common or even abundant in most of the slides I have examined, though usually imperfectly preserved. Other observers report some siliceous but mostly calcareous types, the latter being in some instances unchanged and in others completely replaced by chert. In many cases the fossils are represented only as faint, shadowy outlines, and, rarely, only by variations in the grain of the chert. The paucity of well preserved fossils, and more especially of siliceous types, is not limited to the cherts of the Mississippi Valley, but seems to be characteristic of cherts generally. The microscopic evidence indicates that the rock is subject to ready and perhaps repeated recrystallizations, even more readily than are the limestones. This recrystallization tends to destroy the fossils present. Not only are the contained siliceous remains affected, but, because of the ready replacement of calcite by silica, the solution and redeposition of silica may result in the gradual replacement of many if not all of the calcareous fossils present in the chert, and may destroy the details of those that remain. Many instances, however, of partially weathered chert are found in which the calcareous fossils have been removed by solution, the resulting molds showing even the minute details.

Chert is occasionally seen grading into limestone, although this is far from characteristic of the cherts of the region as a whole. As a rule there is a sharp line of demarcation between the two. The microscopic evidence does not indicate with certainty whether this gradation represents a replacement of limestone by chert, or an original mixture somewhat modified by recrystallization. I am inclined to the latter interpretation, which the bulk of the evidence seems to favor. Such admixtures are by no means unknown or even uncommon in other parts of the world.

The use of the term "cotton rock" in this paper differs from that of earlier writers. It has been used by all the present authors, apparently, for a rock intermediate

between chert and limestone, and has been defined by Agar (p. 149) as "mixed chert and limestone." As used by Broadhead, Jenney, Buckley and Buehler, Laney, Siebenthal and myself, however, the term "cotton rock" refers merely to a somewhat weathered chert. As described by me, it is a chert that has become whitened, dull and somewhat chalklike and porous, as a result of partial weathering. The analysis of a specimen collected by Jenney shows essentially the same composition as that of unaltered chert from the same locality. Both are almost free from lime.

As opposed to the views of Fowler and Lyden, there is considerable evidence to show that both the Grand Falls chert and the Short Creek oolite are well defined and persistent members of the Boone formation; that the warping of the Grand Falls chert was probably the chief factor in determining the character of the deformation in the rocks overlying it; and that this chert is therefore in large measure responsible for the structural features that have led to the concentration of ores in this region. This subject, however, cannot be discussed at this time.

G. M. Fowler and J. P. Lyden (written discussion).—We are very pleased that Mr. Smith has taken time to add his interesting discussion to this paper, as he was one of the early investigators for the U. S. Geological Survey in this district and is the author of several geologic publications regarding it.

It is clear that Mr. Smith believes that there was but one period of regional deformation and is attempting to tie the chert and orebodies to it. We have differentiated three periods. On page 113 we state that "The chertification is pre-Chester in age, as attested by the fact that the Boone was deformed and chertified in some degree from top to bottom on these earlier zones of deformation . . ." This definitely separates the pre-Chester deformation and chert from the jasperoid and orebodies.

On page 128 we state the age of the ore deposits and jasperoid as post-Pennsylvanian. They are related to the second period of deformation, which caused reopening along the same general zones of adjustment of the first period with additional deformation. The Miami shear trough is mostly post-Pennsylvanian in age and belongs to the second period. The third period of deformation was subsequent to the ore deposition.

Mr. Smith says, "There is evidence that the cherts are not only older than the deformation of the region, but older than the stylolites of the limestone." Figs. 11, 15*a*-2, 15*a*-3 and 32 show stylolites older than the chert.

Stylolites are common in the limestone throughout this district. Their formation was probably a continuing process, as it is not uncommon to find older stylolites cut by younger ones. We regard some of them as older and some younger than the chert.

The term "cotton rock," as used in this district, is as we have described it. "Cotton rock," as described by Mr. Smith, is found in drill holes and mine workings and does not differ essentially from the weathered material. It is the same material whether the limestone was removed by underground solutions or by weathering. In the Joplin District Folio, of which Mr. Smith is co-author, the following statement occurs: "Chert approaching cotton flint has been noted in the cuttings from the Freeman Foundry well, Joplin, at intervals to a depth of over 300 feet."

In the last paragraph Mr. Smith says: "There is considerable evidence to show that both the Grand Falls chert and the Short Creek oolite are well defined and persistent members of the Boone formation." In the Joplin district the Short Creek oolite is quite persistent, but in the Oklahoma-Kansas field it has been found only in a few scattered areas. The Grand Falls chert is related to zones of deformation and is quite extensive in some of the major zones, such as, for example, the Joplin anticline. This chert is neither well defined nor persistent in the Oklahoma-Kansas field.

W. A. Tarr,* Columbia, Mo. (written discussion).—Fowler and Lyden say that I make "numerous unsupported statements" regarding my theory and the theories of others as to "the origin of the chert and chert breccias." May I be permitted to suggest that these authors read my published work, based on many years of study of chert and flint, in which they will find the evidence I have given to support my views. That they are not investigating the problem with the usual scientific approach is shown by their statement that they "are not particularly concerned with Dr. Tarr's theories."

Since their reply to my criticism of their earlier paper [*Trans.* A.I.M.E. (1932) **102**] I have been a member of a party conducted by Mr. Fowler in the Barr mine of the Tri-State district, and sought in vain to secure from him any explanation of the features of the chert, which he and Lyden claimed I misinterpreted. On that trip, I became even more convinced that my interpretation given in 1933 was correct.[26] Residual clays resulting from the solution of limestone along joints and bedding planes and blocks of chert and limestone in residual clays of typical sink-hole deposits are observations I made that are unmistakable evidence that the solution of the limestone along the chert horizons produced the brecciated zones which later became the seat of the sulfide mineralization. There are not two generations of the chert (which unquestionably in my mind is a syngenetic deposit), and the so-called cotton rock is merely the calcareous outer portion of the chert, which was formed as the chemical deposition of the silica was decreasing and more calcareous material was being incorporated.

Fowler and Lyden admit that they do not know the source of the silica (p. 129), and evidently refuse to believe that anyone else may have an explanation. Any theory of chert formation that is unable to account for the source of the silica is of little value.

Their own statements do not agree. For example, on page 132 they say, referring to chert along a horizon: "the horizon may be quite lacking in chert a short distance in from the face of the bluff," yet on pages 108, 110 and 125 they cite insoluble residues, a geologic section and churn-drill holes as evidence that the Boone formation contains chert everywhere in the area!

They quote Mansfield's views of the origin of chert given in 1927, instead of his later views published in 1931.

Fowler and Lyden date the chert as Mississippian, put the mineralization as post-Pennsylvanian, and suppose all "came from the same general source," though separated by more than a geologic period!

Mr. Gregory can hardly dispose of one of the prevalent theories of the origin of chert (a problem being intensively studied by many) by saying it "will have to be abandoned," especially when he has merely rehashed a 75-year-old theory. He is a chemist, and yet hides behind such a term as "silicic acid."

Professor Agar has described as two varieties of chert parts of one, as his photographs and descriptions show. Variations in texture, color and composition within a unit mass of limestone, dolomite or chert are of world-wide extent and do not prove that the associated materials are of different age. Transitions are common in all sedimentary rocks.

F. E. Gregory (written discussion).—Dr. Tarr's statement that I am hiding behind the term "silicic acid" is somewhat vague in its imputation. A rational explanation of the mode of transportation of the silica found in cherts and other types

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* University of Missouri.

[26] W. A. Tarr: Reference 10.

of deposits has always offered difficulties. Kahlenberg and Lincoln[27] found that sodium metasilicate is hydrolyzed into colloidal silica and sodium hydroxide. F. W. Clarke[28] states that the silica in solution in natural waters is present in the colloidal form. Further, it is common knowledge that the colloidal silica on being freshly precipitated contains water in loose combination, and that SiO_2 is the anhydride of the various silicic acids. Silica is most certainly not dissolved and transported in a water medium as the anhydride, a condition which Dr. Tarr seems to infer.

As to the age of the theory set forth in my paper, I have no comments. The inference is somewhat irrelevant.

W. M. Agar (written discussion).—In view of Dr. Tarr's remarks concerning the varieties of chert, I wish to add a few observations on the chert and its banding. The different shades of gray and dull white that occur in the bands of the nodular chert relate largely to the amount and to the state of aggregation of the organic matter present; and to a much smaller degree to the size of the fossil organisms and the amount of carbonate present.

The organic coloring matter occurs in several different ways and in different shades of yellow-brown or black. These are: (1) an evenly distributed yellow-brown stain in chalcedony surrounding clear areas of chalcedony or quartz. These clear areas contain a few black dots and are apt to be outlined by the black dots. (2) Dark brown or black spots throughout the chert except for clear areas of slightly coarser grained quartz or chalcedony. The fossils contain the largest number of black dots in this type. (3) The chert is clear except for light brown spots disseminated through the fossils. (4) The body of the chert is a smooth yellow-brown and the fossils full of black dots. (5) The chert is clear except for an evenly distributed yellow-brown color in the fossil fragments.

These various modes of aggregation are not related to the numbers of fossils nor to the percentage of quartz and chalcedony. Sometimes the centers of fossils or the interfossil spaces are filled with fibrous chalcedony, at other times with microcrystalline quartz. The change from one color to another takes place within a millimeter or less along an irregular boundary, and a single, small fossil may extend from one band into another and partake of the characters of both.

The color bands do not depend upon the form which the crystallized silica gel has assumed, nor are they related to tension cracks formed when the gel set. The only signs of such structures are the curved, triangular areas with inward convex boundaries, which look like the voids between closely packed spheres, and other irregular contraction forms that usually are filled with coarser silica—either chalcedony or quartz—free from impurities. The banding, therefore, appears to be due to segregation of the impurities, probably resulting from diffusion.

Variations in the amount of carbonate present in the chert, usually combined with different states of aggregations of the organic matter, account for some of the banding of the outer part of nodules, where the silica gives way to purer and purer limestone. When no organic coloring matter is involved, the microscope may not reveal the boundary line between white "cotton rock" and limestone even though it is very distinct macroscopically. This is true of the outer border of the nodule pictured in Fig. 4.

None of the above described features correspond to the difference between the two types of chert designated as *younger* and *older*. It is true that the boundary between these types is not always regular, but their texture, composition, coloring, and usually their content of fossils contrast sharply. The younger chert holds fragments of the older and often penetrates it in veinlets.

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[27] L. Kahlenburg and A. T. Lincoln: *Jnl. Phys. Chem.* (1898) **2**, 77.

[28] F. W. Clarke: U. S. Geol. Survey *Bull.* 770 (1924) 195.

Other authors have noted two types of chert in this district before and my microscopic study indicated to me that this was correct. Its importance rests solely on the fact that it indicates the presence of brecciated chert before the main part of the chert came into existence.

The evidence cited, together with that indicating a replacement origin for the chert, cannot be dismissed merely by recalling the rather generally known fact that sediments vary from place to place.

G. M. Fowler and J. P. Lyden (written discussion).—We have read most of Dr. Tarr's publications regarding chert and flint and find many theories but very few records of observed facts regarding the Tri-State district. Our paper is confined almost exclusively to field observations in this district, as is mentioned many times throughout the paper. Dr. Tarr's theories may appear to explain facts regarding other regions, but he applies them to conditions in this district where it is very evident to us that he is unfamiliar with the occurrence of the chert, chert breccia, and ore deposits. We specifically cited numerous field observations and gave our evidence and interpretations regarding them. We cannot but wonder what Dr. Tarr's interpretation would be of the same observed facts. For example, what explanation would he give for the unquestionable fact that a bed that is practically all chert in an area where usually there is ample evidence of structural deformation often is predominantly limestone in areas of little deformation. Sometimes this transition is very abrupt and sometimes gradual. It is because Dr. Tarr bases his conclusions on theories that do not explain the facts as we have observed them in this district that we are not particularly concerned with his theories.

Dr. Tarr was a member of a group of more than fifty who spent less than four hours in the Barr mine in March, 1934. As one (Fowler) of four guides with a group of this size it was impossible to give him very much individual attention. Conflicts of opinion regarding our published statements were scarcely mentioned during the trip. It would take days instead of several hours for anyone to gain a practical knowledge of the chertification, chert breccia, and ore deposits, and develop theories on his observations.

Our statements on pages 7, 9, 24 and 31, which Dr. Tarr criticizes, refer to different phenomena instead of one, as he infers. Those on the first three pages mentioned refer to many horizons or all of the Boone, which is nearly 400 ft. thick, and the one he quotes from page 31 refers to one horizon within the Boone.

Between the areas of more intense deformation a stratum or two may be chert-free throughout small areas, but any horizon embracing several strata is almost certain to reveal a little chert. It is obvious that some limestone beds chertified much more readily than others. In the Oklahoma-Kansas fields beds G and H are most notable in this respect, as more chert is found in them over a larger area than in other beds.

Silica-bearing solutions sometimes migrated long distances from the principal centers of deformation, along bedding planes or stylolite partings that were disturbed only by slight movements, and replaced the limestone with chert in the form of thin sheets or thin nodular layers. This condition is particularly common in the Ozark region in areas of minor deformation.

These three paragraphs explain Dr. Tarr's statements that " . . they cite insoluble residues, a geologic section, and churn-drill holes as evidence that the Boone formation contains chert everywhere in the area."

Dr. Tarr says, "There are not two generations of . . . chert." Two generations were found by Buckley and Buehler,[29] by F. B. Laney[30] and by Gregory and Agar, our co-authors. All of these men are very familiar with the chert of this district.

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[29] E. R. Buckley and H. A. Buehler: Reference of footnote 19.

[30] F. B. Laney: Reference of footnote 18.

Mansfield's earlier paper was quoted because it gives concisely the principal theories regarding the origin of chert.

We are not particularly disturbed because we are unable to locate the source of the silica that formed the chert. We are certain that most of the chert is secondary and our evidence to date suggests a deep-seated source. Certainly there is nothing inconsistent in assuming that both the chert and the ore may be from that general source, although they are separated by more than a geologic period.

All of the discussions have added greatly to the interest of the paper and have emphasized points that might have passed unnoticed. Doubtless many of the facts we have presented in our several papers could have been stated more clearly, and perhaps in a final paper we can state them more concisely. However, we do feel that any open-minded observer can check our observations for himself, if he is sufficiently interested to spend the time and take the trouble to do so. We realize that it is futile to attempt to convince anyone against his will, by an exchange of words at long range, or by oral argument over the explanation of a few scattered observations made at long intervals on hasty visits to a few mines. We do not wish to appear to be prolonging a needless argument.

All of the specimens described in our papers are in the possession of Prof. W. M. Agar, at Columbia University in New York City, as it seems to be the most satisfactory and generally available place to deposit them so that they may be examined and studied by others.

Disconformity between the Keokuk and Warsaw Formations*

Since the publication of this paper in 1934 our further studies reveal additional evidence regarding the nature of the contact between the Warsaw and Keokuk formations in and near the Oklahoma-Kansas mining field. Earlier investigators describe a stratigraphic break between these formations in parts of southwestern Missouri and elsewhere. In the Oklahoma-Kansas mining field the strata comprising the Keokuk and Warsaw formations are essentially parallel and there is little or no evidence of a hiatus between the two formations. However, in sporadic areas within the mining field and in several detached areas west of the field, which we have had occasion to study, erosion cut into the horizontal Keokuk surface before the Warsaw was deposited on it and removed part or all of K and L beds and the upper part of M bed to a total depth of 45 ft. below the top of K bed—the top of the Keokuk. J bed, as described on page 110, is essentially uniform in thickness and character throughout the field and nearly everywhere is an excellent marker horizon. In the areas where the underlying beds have been eroded, the section below the normal 4 to 5 ft. of J bed, down to the old erosion surface, is filled with material similar in character to that in J bed but generally more shaly near the base, especially in the deeper places. In a few small areas J bed, as we know it, is absent and H bed rests directly on K bed. The distance from the bottom of H bed to the top of N bed is nearly constant throughout the field.

We recently found oolite in the above described material from the bottom part of the Warsaw formation. It occurs sparingly in very small lenses in a few mines and is distinct from the oolite stratum in L bed noted on page 110. Other investigators found an oolite horizon near the Warsaw-Keokuk contact and designated it as the Short Creek member. They are not always in accord as to which of these two oolite horizons should be so designated.

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* Received at the office of the Institute April, 1935.

Geology of Elk City Mining District, Idaho

With Special Reference to the Structural Setting of the Veins

By P. J. Shenon* and J. C. Reed*

(New York Meeting, February, 1933)

The Elk City district is in north-central Idaho about 60 miles east of Grangeville and near the headwaters of the South Fork of the Clearwater River (Fig. 1). At the height of its boom in the early sixties, Elk City had a population of more than 2000 people.[1] Published estimates of the placer production from the district range from \$10,000,000 to \$18,500,000. Although the first quartz-vein location was made as early as 1870, very little gold was extracted from quartz ores until after the completion of the American Eagle mill in 1902. Between 1902 and 1932 a total of from \$750,000 to \$1,000,000 was taken from about six properties.

General Geology

Distribution of Rocks

Banded gneiss (Fig. 2) is the most abundant bedrock in the Elk City district. It is interbedded with schist and quartzite and in some places these rocks have been intruded by sills and dikes. Banded gneiss prevails in the western part of the area whereas schist prevails to the southeast. Augen gneiss occurs for the most part as irregular bodies, which lie transverse to the trend of the banded gneiss and schist. It is largely confined to two areas; one of which extends from east of the American Eagle mine westward as far as the Black Pine mine, a total distance of about five miles, and another area of about two square miles in the vicinity of the California-Idaho placer mine. Quartzite is fairly abundant. In addition to the bands of the latter interbedded with gneiss and schist, some large lenses crop out in the southeastern part of the district near the southern contact of the area underlain by granodiorite. Granodiorite crops out over a large area and extends northeastward

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* U. S. Geological Survey, Washington, D. C.

[1] H. H. Bancroft: Bancroft's Works, **31**, 241. The History Company, 1890.

A. L. Flagg: The Elk City Mining District, Idaho County, Idaho. *Trans.* A. I. M. E. (1914) **45**, 113–122.

beyond the map limits. Lake and stream deposits occupy the wider valleys, and lake deposits cap some low-lying hills adjacent to the wider valleys.

Quartzite

Only poor outcrops of quartzite were seen in the district, and its presence was ordinarily detected by float. For this reason, and because

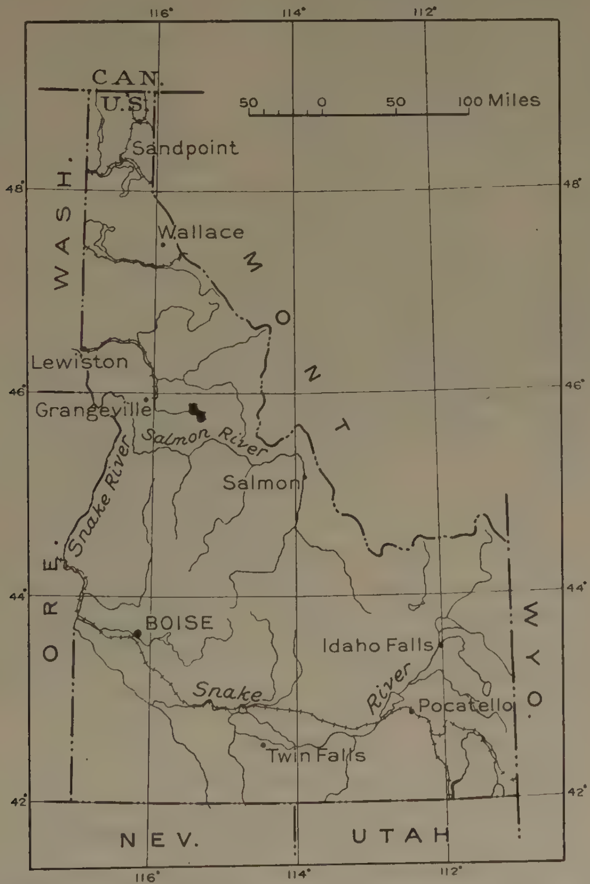

FIG. 1.—INDEX MAP OF IDAHO SHOWING LOCATION OF ELK CITY DISTRICT.

of its massive character, very few structural observations could be made on it. Due partly to included impurities, the rock ranges in color from white through gray to brown or red.

Ordinarily the quartzite is characterized by a rather coarse granular texture. The original material has been completely recrystallized and the result is a vitreous mass which in some places closely resembles

crushed vein quartz. Under the microscope the granular texture is not apparent, although the quartz grains have very irregular boundaries.

In addition to quartz the rock contains minor amounts of potash feldspar, both microcline and orthoclase, muscovite, biotite, zircon and magnetite. The feldspar is typically, but not always, in rounded grains

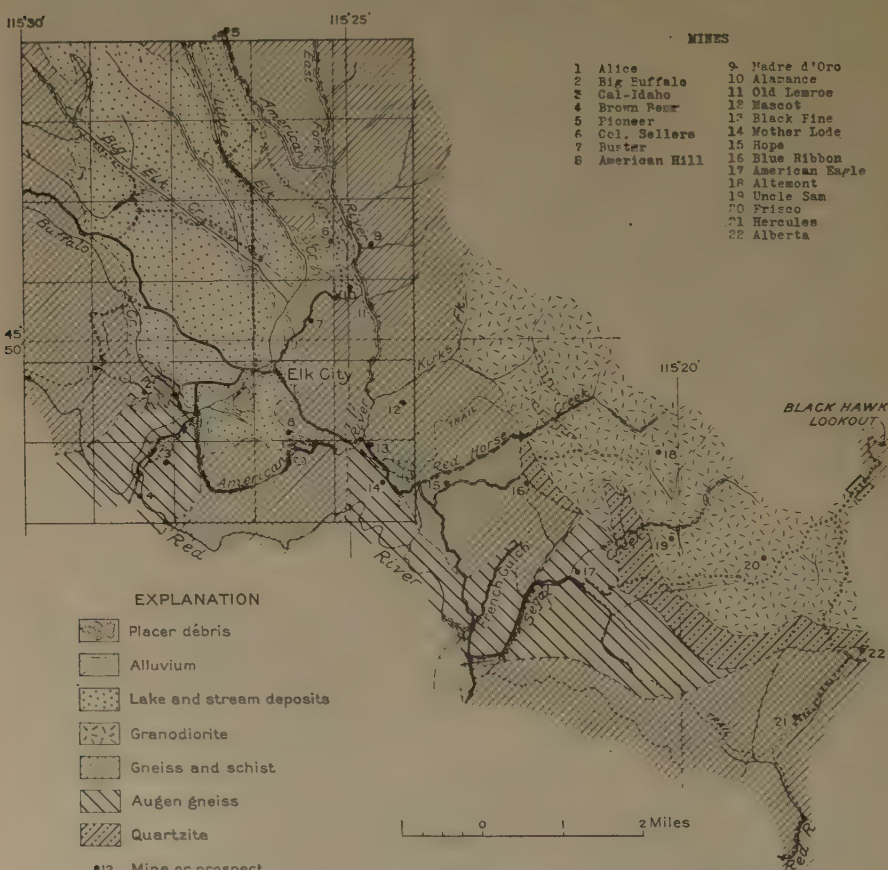

FIG. 2.—GEOLOGIC MAP OF ELK CITY DISTRICT.

along contacts between quartz areas. This may indicate that at least part of the feldspar has been added to the rock from magmatic sources. Some of the feldspar has altered to a claylike mineral.

Schist and Banded Gneiss

Several varieties of schist occur in the Elk City district, ranging from rocks composed largely of quartz grains with little feldspar to rocks rich in feldspar. Both biotite and muscovite are abundant in nearly

all of the schists. In the quartzitic schists there is a strong tendency for these minerals to occur along boundaries of quartz grains. Microcline is fairly common in the more feldspathic varieties impregnated by granitic materials. Almost all of the schistose rocks contain apatite and zircon, and some of them carry epidote, sillimanite, tourmaline and garnet.

The term "banded gneiss" is applied here to rocks that have alternate light and dark bands, in order to contrast them with other gneisses that contain large lenticular crystals or augen. The term is used advisedly in preference to "injection gneiss," because it does not imply the manner in which the banding was developed. The proportions of light and dark bands differ greatly—from schistose rocks with a relatively few imperfect light-colored bands as one extreme to gneissic granodiorite with a few irregular dark bands as the other. The most pronounced banding is shown in the rocks intermediate between the two extremes.

Quartz, biotite and muscovite are the most abundant minerals in the poorly banded schistose gneisses. Quartz grains commonly constitute over 50 per cent of the rock. Oligoclase, biotite and muscovite account for much of the remainder and microcline is present in some specimens. Magnetite, apatite and titanite are the usual accessory minerals and sillimanite, tourmaline and garnet are less common. The well banded gneisses are made up mostly of oligoclase and quartz. The oligoclase is commonly more abundant than quartz, biotite in places exceeds muscovite, and microcline, titanite, and apatite are more abundant than in the schists. In the granitic gneisses oligoclase also exceeds quartz. Considerable green hornblende and microcline are present.

The banded gneisses have a granular texture. With the exception of the micas and some of the accessory minerals, none of the grains are euhedral. The micas, particularly biotite, show a marked parallelism in the direction of the elongation of the plates. The quartz and feldspar grains, which make up the greater part of the banded gneisses, are very irregular. Both plagioclase and microcline extend into embayments in some quartz grains in a manner commonly described as absorption boundaries, and both feldspars cut some of the quartz grains, thus indicating that some of the quartz is older than these feldspars. In general, the grains of quartz and feldspar have cross-sections of less than 1 sq. mm. Some of the microcline crystals, however, are very large and where they are abundant the rock is classed as augen gneiss. The microcline is clearly later than the plagioclase. It crosses grains of plagioclase and sends apophyses into plagioclase crystals. The microcline borders are sharp, although there is usually a narrow zone between the plagioclase and microcline that has anomalous extinction. Some biotite and muscovite grains have irregular boundaries against feldspars, and in places the feldspars have formed graphic intergrowths where they have encroached on the biotite and muscovite.

Titanite has formed for the most part as long lathlike crystals along grain boundaries of other minerals and in places lath-shaped grains cut across several different grains of plagioclase, thus strongly suggesting that the titanite has formed after the plagioclase. Numerous well rounded grains of apatite and a few grains with euhedral outlines have formed mostly along the contacts of other minerals. Zircon, on the other hand, is in most places included in grains of other minerals, particularly in biotite.

Most of the banded gneisses are almost free from alteration. Sericite has developed along fractures in feldspar, and fine-grained epidote and chlorite in places replace biotite. Large grains of epidote in some of the rocks appear to have formed earlier than the fine-grained variety.

Augen Gneiss

Augen gneiss differs from banded gneiss principally because it contains numerous large crystals of microcline and knotlike lenses of aplitic material. No sharp line can be drawn between it and banded gneiss containing a few large microcline crystals on one hand and with gneissic granodiorite with large phenocrysts of microcline on the other hand.

Oligoclase, microcline, quartz and biotite are the more common minerals. Some muscovite is generally present and green hornblende occurs near granodiorite contacts. Apatite, titanite, zircon and magnetite are the most common accessory minerals. Thin sections of the rock show a decided gneissic structure where biotite is abundant. Where biotite is scarce and oligoclase and quartz are the principal minerals the rock has a granular texture and the grains are all about the same size. The crystals of microcline range in length from about 0.5 mm. to over 10 cm. in extreme cases, but probably do not average more than 2 or 3 cm. Bands of biotite and other minerals bend around the larger crystals, and in these places the bands are closely spaced and the rock has a decidedly squeezed appearance. Microcline cuts grains of quartz, oligoclase, biotite and muscovite, and has clearly formed later than these minerals. It has sharp, clean-cut boundaries although there is commonly a narrow transition zone between it and the replaced mineral. The microcline crystals are not crushed around their borders or elsewhere, although the other minerals surrounding them are fractured and display pronounced undulatory extinction. The larger crystals of microcline commonly contain grains and fragments of plagioclase, quartz, biotite and muscovite, and in many places smaller crystals of microcline occur around the edges of the larger crystals. The plagioclase inclusions in the microcline are in general greatly altered whereas the microcline is relatively free from alteration.

The knotlike lenses of aplitic material range in thickness from slight swells in well defined bands to very pronounced lenses 1 or 2 cm. across.

On an average they are not as large as the augen of microcline. The lenses are made up principally of oligoclase, quartz and microcline. In general the microcline in the aplitic lenses has not grown much larger than the other minerals associated with it. The augen gneiss normally is quite free from alteration. Some sericite is usually evident along fractures in oligoclase, and biotite in some places is slightly altered to chlorite and epidote. Near veins, however, there is considerable hydrothermal alteration.

Granodiorite

The normal granodiorite is a coarse-grained rock with a decidedly porphyritic texture and a distinct gneissic structure near contacts with gneisses. Contacts between granodiorite and the gneisses are gradational and hence formational boundaries were arbitrarily set in the field.

Oligoclase, quartz, microcline, green hornblende and biotite are the most abundant minerals. Titanite and apatite are abundant accessories, and zircon, epidote, magnetite and garnet are present in smaller amounts. Green hornblende is the characteristic dark mineral of the normal granodiorite, although biotite is abundant where the granodiorite has pronounced gneissic structure. Like the gneisses, the granodiorite in general is very slightly altered. Some sericite, chlorite, calcite and fine-grained epidote are commonly present.

Sills and Dikes

Several basic sills, some as much as 200 ft. thick, were observed in the eastern part of Elk township and just east of the township. They have been recrystallized to hornblende schist and, therefore, are older than the unfoliated andesite dikes which are described below. A thin section shows one typical specimen to be composed of about 75 per cent hornblende and 25 per cent andesine.

Andesite dikes have a wide distribution in the district. They were seen at a few places on the surface and were cut by many of the mine workings. They are not foliated and in some places cross quartz veins and are therefore younger. Most of the dikes range up to 30 ft. in width, and none was traced along its strike for more than 200 ft. Their color range includes light gray, dark gray, greenish gray, and, in a few instances, white. The dikes are holocrystalline and may be either fine grained or medium grained. Most of them are porphyritic.

The feldspars are typically zoned, the usual range being sodic oligoclase to calcic andesine. Some dikes contain albite, and still others labradorite. The dark mineral is either brown hornblende or biotite, or both. Quartz is present ordinarily as an accessory. Some dikes contain amygdules of prehnite.

Many of the dikes are more or less altered. Typical alteration products are calcite, sericite and chlorite. The very light-colored dikes appear to be more altered than the others.

Lake and Stream Deposits

The lake and stream deposits that conceal the bedrock over large areas of the district consist principally of gravel, sand and clay. These deposits must be at least several hundred feet thick locally, and in some placer pits well over 100 ft. of the material is exposed. The distribution and character of the beds, together with physiographic evidence, show that much of this material was deposited in shallow lake waters. However, during part of its history, the Elk Valley depression was a broad, flat swamp land, as is attested by the occasional lignitic and ferruginous beds. In one place about four feet of tuffaceous material is exposed.

Geologic History

The oldest rocks of the Elk City district are metamorphic derivatives of part of a thick sedimentary series, but there is no direct evidence in the district as to their age. It is quite possible that they correlate with the quartzitic and argillaceous Belt rocks, which are widespread in northern Idaho. The basic sills in these rocks at Elk City are similar to those in Belt rocks described by Anderson[2] in the region around Orofino, which he referred to the late Algonkian because of their resemblance to the basic sills described by Schofield[3] in the Cranbrook area, B. C. Such sills are common also in the Belt rocks of Shoshone and Benewah counties, Idaho.[4]

The first event recorded in the district after the intrusion of the sills is a period of deformation and intense metamorphism. The metamorphism may have been due in part to folding, but most certainly the intrusion of the Idaho batholith had a profound effect. Granitic rocks, which without doubt may be referred to the Idaho batholith, clearly cut the folded sediments. Thus, at least part of the deformation of the sediments was earlier than the intrusion of the batholith, and possibly

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[2] A. L. Anderson: The Geology and Mineral Resources of the Region about Orofino, Idaho. Idaho Bur. Mines and Geol. *Pamphlet* 34 (1930) 12.

[3] S. J. Schofield: Geology of Cranbrook Map-Area, British Columbia. Can. Geol. Survey *Mem.* 76 (1915) 68–70.

[4] J. T. Pardee: Contributions to Economic Geology, 1910, Pt. I. U. S. Geol. Survey *Bull.* 470 (1911) 47.

F. C. Calkins and E. L. Jones, Jr.: Contributions to Economic Geology, 1911, Pt. I. U. S. Geol. Survey *Bull.* 530 (1913) 80–81.

J. B. Umpleby and E. L. Jones Jr.: Geology and Ore Deposits of Shoshone County, Idaho. U. S. Geol. Survey *Bull.* 732 (1923) 9.

A. L. Anderson: A Geological Reconnaissance in the St. Maries Region, Idaho. Idaho Bur. Mines and Geol. *Pamphlet* 30 (1928) 7.

represents an early stage of the diastrophism which culminated in the intrusion and consequent metamorphism. The quartz veins and their mineralization may be accounted for by waning stages of the same igneous activity.

The age of the Idaho batholith is doubtful. Similar rocks, which may belong to the same batholith in western Montana, have been generally classed as late Cretaceous or early Eocene;[5] however, evidence in central Idaho may point to an earlier age.[6]

The region was deeply eroded to a surface of low relief after the intrusion of the batholith and the thick cover of sedimentary rocks was removed to expose granitic rocks over a very large area in central Idaho. Erosion was actively revived by the uplift of this surface and as a consequence it was greatly dissected. Remnants of it in places stand at elevations of over 8000 ft. A temporary base level, perhaps local, was reached during at least one stage of the uplift, for a pedimentlike surface appears in places between the high peneplain and the present valley bottoms.

In Miocene time great floods of Columbia River lava inundated the lower parts of the region. The dammed streams from the higher mountains ponded against the faces of the great flows and the sediments that collected were subsequently buried by later flows. Since then, and possibly in part during the time of the lava floods, faulting and warping formed certain basinlike depressions, which later were partly filled with unconsolidated sediments. The intrusion of andesite dikes and related rocks of the district may be connected with Miocene igneous activity, but the relationship was not established.

The drainage was again revived and eventually the trunk streams tapped the enclosed basins or established new diversion channels, and erosion correspondingly proceeded headward along the valleys and removed a part of the lake beds. Before the Pleistocene, the Salmon and Clearwater rivers had cut very deep canyons well below the level of the Columbia River lava. After the canyons were cut almost to their present levels, rhyolitic flow-breccia and tuffs were extruded in some of the canyons, and remnants of them, partly covered by glacial till, still remain in Sheep Creek Canyon in the Buffalo Hump quadrangle. In the Pleistocene epoch the highlands surrounding the Elk City district were extensively glaciated, and glaciers pushed well down into the valleys. However, evidence of glaciation was not found within the Elk City district, and, furthermore, it is doubtful whether the South Fork of Clearwater River was ever dammed by Pleistocene ice or its deposits.

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[5] A. Knopf: Ore Deposits of the Helena Mining Region, Mont. U. S. Geol. Survey *Bull.* 527 (1913) 33–34.

[6] C. P. Ross: Mesozoic and Tertiary Granite Rocks in Idaho. *Jnl. Geol.* (1928) **36**, 673–693.

The normal course of erosion does not appear to have been interrupted since the Pleistocene. The sharp canyon of the South Fork has incised itself headward to a short distance above the confluence of Red and American rivers, and stream erosion is still very active in the region.

Veins

Quartz veins, valuable principally for their gold content, are numerous in the Elk City district. They occur in all of the formations of the bed-rock series although thus far the most productive mines have been found in gneiss and schist. Practically all of the mines are in a zone less than 2 miles wide adjacent to the granodiorite contact.

The quartz veins range up to a maximum of 20 ft. in thickness and from a few feet to at least 300 ft. in length. In general, the quartz does not occur as single continuous bodies but rather as a series of slightly curved lenses (Fig. 3). The lenses are nearly all separated from the wall rocks by dark gray gouge, which has developed along faults essentially parallel to the veins. Other faults at wide angles to the veins have offset orebodies considerable distances in some mines. At the American Eagle and Blue Ribbon mines, for example, cross faults have caused displacements of over 100 ft. The fault movements have produced considerable brecciation in both veins and wall rocks.

The principal hypogene ore minerals are pyrite, sphalerite, chalcopyrite, tetrahedrite and gold. Sylvanite has been reported by Thomson and Ballard.[7] Supergene covellite and chalcocite are common near the surface. The ore minerals are distributed throughout the veins although they tend strongly to concentrate in shoots. Some sulfides and gold have been introduced into a narrow zone of hydrothermally altered wall rock next to the veins. The altered zone contains considerable calcite, quartz and sericite along fractures and as irregular patches. As shown by the presence of sulfides in many outcrops, oxidation is in general incomplete even at the surface, but under special conditions, sulfides are partly oxidized at depths of over 200 ft.; for example, some oxidation is evident near the faults on the lower level of the American Eagle mine, and Thomson and Ballard[8] report a narrow streak of oxidized ore extending from the surface to a depth of 275 ft. in the Buster mine.

The age of the ore deposits in the Elk City district cannot be fixed very closely. Some of them occur in the granitic rocks of the Idaho batholith and in places lake beds of probable Miocene age rest on an old erosion surface that has cut a number of veins. Therefore, the veins were formed after the Idaho batholith, or parts of it, had solidified and before the Miocene lake beds were deposited.

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[7] F. A. Thomson and S. M. Ballard: Geology and Gold Resources of North-central Idaho. Idaho Bur. Mines and Geol. *Bull.* 7 (1924) 67.

[8] F. A. Thomson and S. M. Ballard: *Ibid.*, 62.

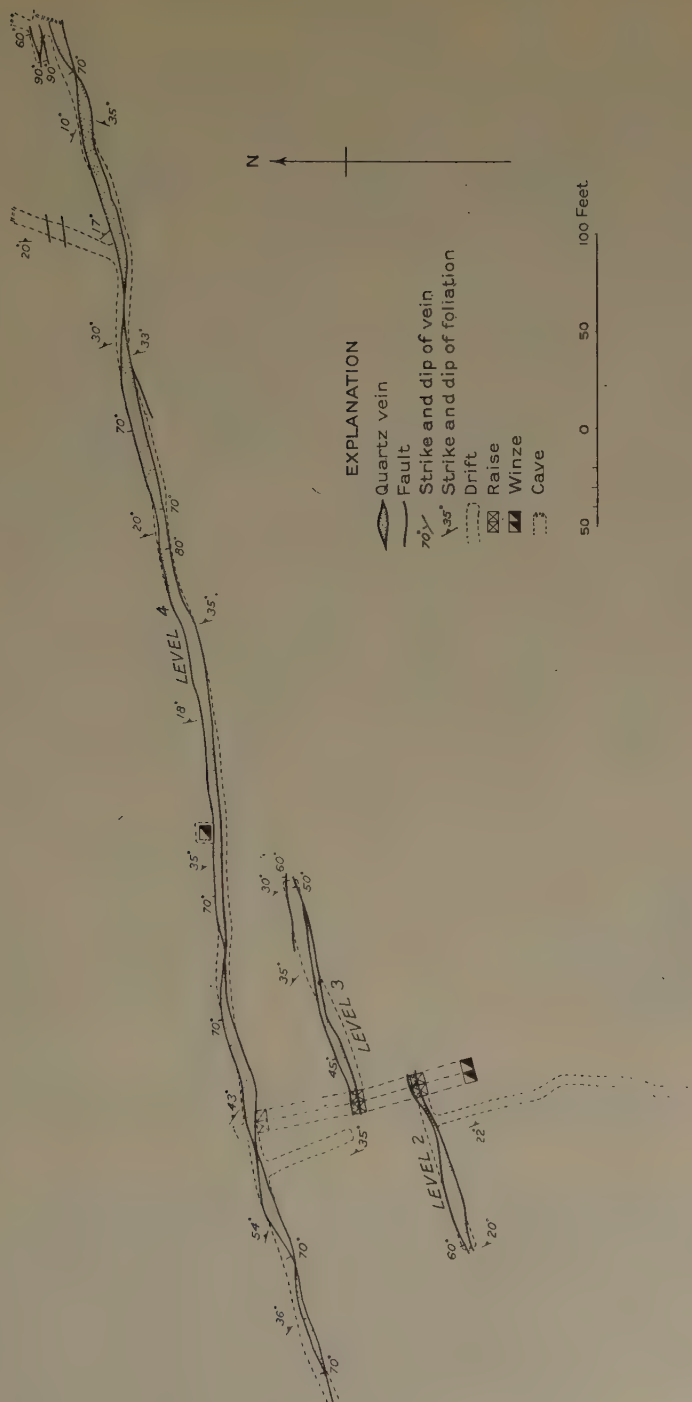

FIG. 3.—PLAN OF PART OF THE BLACK PINE MINE.

Structure

Nearly all of the quartz veins throughout the Elk City district cut the strikes of the foliation of the country rocks at angles approaching 90°. The veins also typically lie nearly normal to a linear element or direction in the plane of the foliation. Most of the veins strike in the northeast quadrant and nearly all of them dip steeply. A more or less consistent

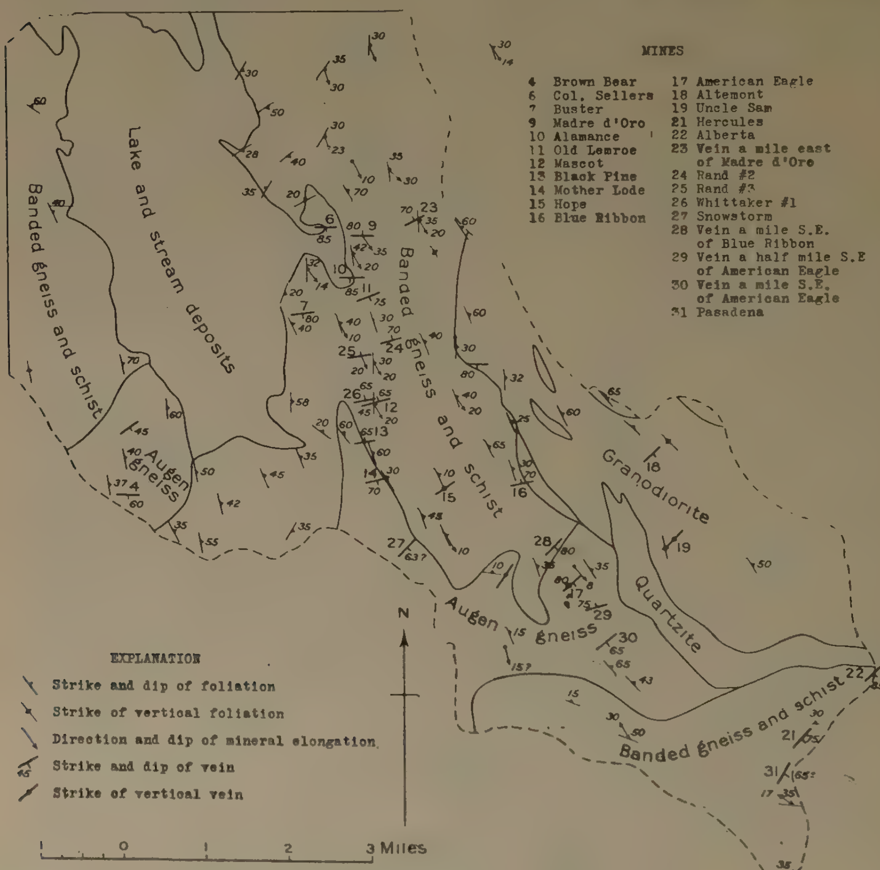

Fig. 4.—Structural map of Elk City district.

change in strike ranges from about N.80°E. in the northeastern part to about N.45°E. in the southeastern part of the district (Fig. 4). The distribution and attitudes of the quartz veins of the district have been recorded by Thomson and Ballard,[9] who say: "The major vein system in the vicinity of Elk City strongly suggests radiation from a central point about 15 miles northeast of that town. The veins apparently

[9] F. A. Thomson and S. M. Ballard: *Ibid.*, 46, pl. 13.

radiate in the southwest quadrant only, whereas the veins in other portions of the surrounding country have various local strikes. Most of the veins are of steep dip."

Structual trends describe arcs concave to the northeast that approximately parallel the granodiorite contact (Fig. 4). The mapped quartzite bands also not only parallel this contact but follow it for half of its extent in the district. In the northeast part, the average strike may be about north-south, in the central part it is about N.20°W., and in the southeast part it is approximately N.75°W. The gneiss in many places is highly contorted and therefore some individual observations differ greatly from these averages. In fact, this is true over considerable areas, such as that between American River and its East Fork, for example, in which the rocks trend northeast.

In most places the foliation dips east toward the concave side of the trend lines, but in a few places, probably owing to minor contortions, dips are in the opposite direction. The range is from 0° to 90°, and the dips differ greatly even at neighboring localities, so that no averages for any parts of the area were attempted.

The foliation of the intrusive granodiorite, so far as it could be determined, corresponds in general with that in the adjacent intruded gneiss, although attention has been called to the fact that there is no definite contact between these rocks, and that the boundary was placed more or less arbitrarily. However, even though the granodiorite intrusive appears to be entirely concordant in the area mapped, definite statements in this connection are not justified because practically nothing is known of the area lying northeast of the Elk City district. Within the district the only apparently discordant contacts are those between augen gneiss and banded gneiss and schist; but, as has been explained, the writers believe that these grade into one another along the strike, so that there is no true structural discordance. The planar foliation of the banded gneiss and schist and augen gneiss apparently coincides essentially with the bedding of these rocks. No banding of the rocks, which might conceivably be referred to original stratification, was observed at an angle with the foliation, and the foliation is practically parallel to the mapped quartzite bands and to several smaller unmapped quartzite bands within the gneiss, which almost surely represent definite sedimentary layers.

In addition to the planar foliation or banding in the rocks, a linear parallelism or mineral elongation was recognized (Fig. 5), which consists of a mutually parallel linear arrangement of the prismatic minerals and of mineral groups lying within any given plane of schistosity, although it also occurs in some rocks in which planar schistosity is lacking. In general, it is parallel to the axes of the minor folds and, like these axes, it is generally more uniform over larger areas than is planar foliation.

The phenomenon has long been recognized in foliated rocks and has been designated by a variety of terms such as stretching, linear foliation, linear parallelism, linear elongation, linear schistosity, and mineral elongation.

Hans Cloos[10] and others have recognized that this "stretching" is widespread in igneous rocks and that a right-angle relationship exists between it and a set of *Q* or cross joints.

In order to avoid genetic implications in this paper, the term "mineral elongation" will be used. The Cloos theory refers the mineral elongation in wall rocks to analogous movements in them occasioned by the deformation they undergo at the time of the emplacement of the adjacent intrusive mass. Accordingly, the "stretching" in the wall rocks and the "stretching" in the intrusive, if the intrusive came in under adequate pressure to deform its walls, should be concordant.

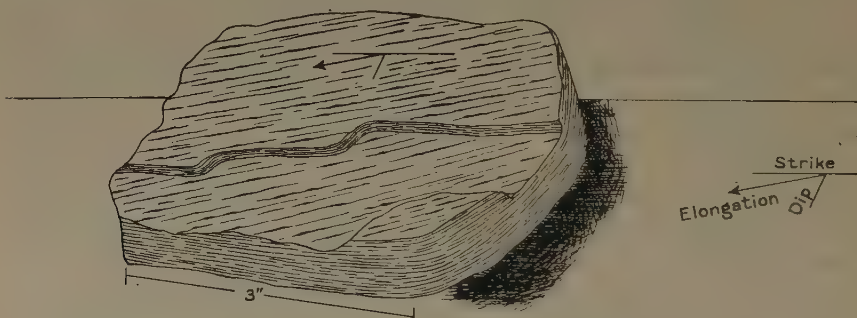

FIG. 5.—SKETCH OF HAND SPECIMEN OF GNEISS ILLUSTRATING LINEAR AND PLANAR FOLIATION.

Most of the observations of mineral elongation in the Elk City district were made on the banded gneiss and schist (Fig. 4). A few were made on augen gneiss and none on granodiorite. This was in part because of the scarcity of good granodiorite outcrops and in part to the fact that the granodiorite does not ordinarily display good mineral elongation, although on most outcrops a plane foliation is apparent.

The trend of the mineral elongation—that is, the projection of the elongation on a horizontal plane—in the northern and central parts of the district is to the southeast, and the pitch is to the southeast at angles ranging between 10° and 30°, at most places about 20°. In the southern part of the district the strike of the elongation is to the northwest, in which direction it pitches at angles up to 30°. Thus a syncline is defined by the mineral elongation and its axial plane trends northeast at about

[10] H. Cloos: Das Batholithenproblem. *Fortschritte* d. Geol. u. Palaeontol. (1923); Bau und Bewegung der Gebrige in Nordamerika, Skandinavien, und Mitteleuropa. *Ibid.* (1928) **7**.

R. Balk: Primary Structure of Granite Massifs. Geol. Soc. America *Bull.* 36 (1925) 679–696.

the valley of Segal Creek. As the mineral elongation lies in the plane of foliation, it follows that the strike of the elongation is more easterly than the strike of the plane foliation, but as the pitch of the elongation is ordinarily 20° or less, it also follows that the angle between the strike of the elongation and the strike of foliation is small.

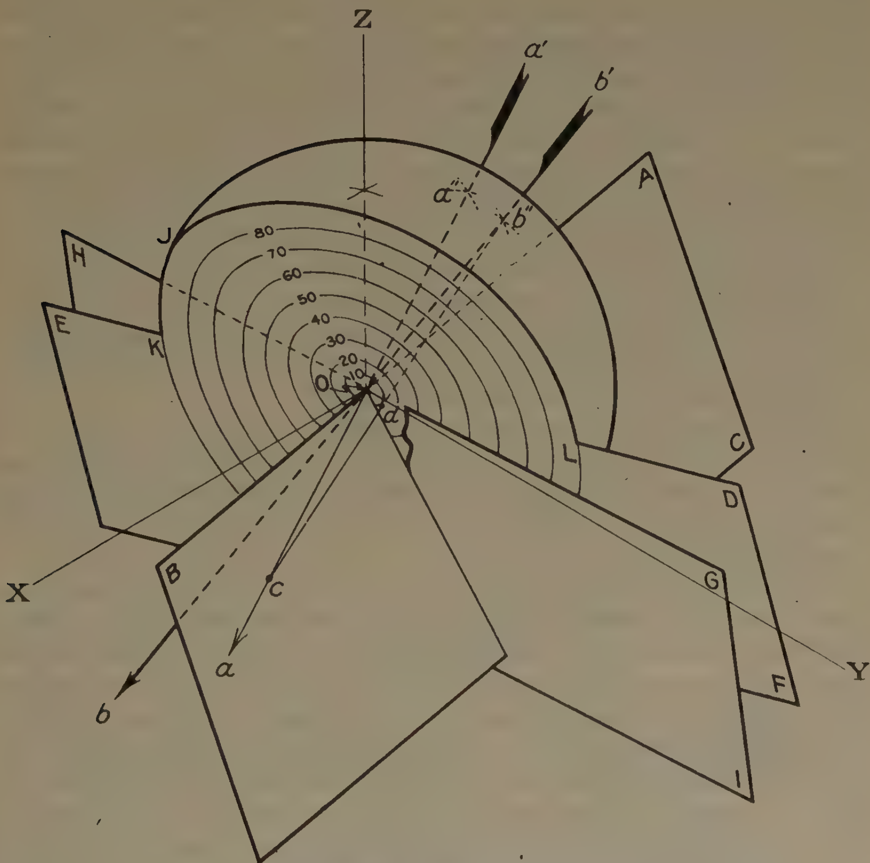

FIG. 6.—ISOMETRIC PROJECTION ILLUSTRATING RELATIONSHIP BETWEEN A VEIN AND MINERAL ELONGATION AND METHOD OF CONSTRUCTION OF A STEREOGRAPHIC PROJECTION.

As is shown in Fig. 4, the quartz veins of the Elk City district bear approximately the same relationship to the mineral elongation as Cloos's *Q* joints do to his "stretching." With the information at hand the writers at present do not wish to postulate a mode of formation of the fractures containing the veins, but merely to point out that in spite of a number of variable factors a nearly right-angle relationship does exist between the veins and the mineral elongation and that variations from this generality are systematic and of an order of magnitude consistent

with the degree of accuracy of the observations, the amount of interpolation necessary, and the changes of attitude due to post-vein movements; and that therefore the relationship between the two is probably genetic.

In order to illustrate graphically the angular relationship between a vein and the mineral elongation, an isometric projection (Fig. 6) has been constructed. Lines OX, OY and OZ are the isometric axes intersecting one another at 90°. OX and OY determine the horizontal plane and OX may be considered the north-south direction and OY the east-west direction in that plane. Plane ABC represents the planar foliation of the gneiss. Its strike is a few degrees west of north, and it dips steeply northeast. In plane ABC lies a linear element, the mineral elongation, shown by line a-a'. If a vein were exactly at right angles to the elongation (a-a') it would occupy the position of plane DEF and the elongation a-a' would also be the direction of the pole of the plane DEF, which by definition is a direction at right angles to a plane.

In the Elk City district, however, a vein and the mineral elongation do not ordinarily lie exactly at 90° to each other. The vein may occupy a position such as plane GHI, in which case its pole b-b' diverges from the mineral elongation by some angular amount.

The true angle of divergence was measured between the direction of elongation and the poles of each of the 24 veins on which the data were available. These results have been plotted on a stereographic diagram (Fig. 7) as a graphic means of showing the variation from a true right-angle relationship.

Fig. 6 shows the method of construction of the stereographic diagram, Fig. 7.[11] The intersection, JKL, is determined between the plane DEF that lies at right angles to the elongation a-a' and a sphere that has its center at the intersection of the isometric axes, 0. (Only the portion of the sphere lying behind plane DEF is shown.) The portion of the plane DEF that is enclosed by the circle JKL is the surface of projection of the stereographic diagram. Point a'' is where the sphere cuts a-a' and c is the point where the front half of the sphere, if shown, would cut a-a'. The point c is the point toward which all points to be shown on the stereogram are projected. For example: b-b', the pole of vein GHI, cuts the sphere at b''. A line between b'' and c passes through plane DEF at d (a portion of plane GHI has been removed here so that point d on plane DEF may be seen). d will appear on the stereogram at an angular distance from 0, the center, depending on the true angle between a-a' and b-b'. Concentric circles representing angles ranging from 0° at the center to 90° on the circumference of the diagram are shown on the equatorial plane of the hemisphere in Fig. 6, and the same circles viewed from c are shown in Fig. 7. The direction of the projection

[11] For a more complete description of stereographic projection see Dana's Mineralogy.

of any vein from the point 0 is the direction of the pole of the vein projected to a horizontal plane.

Thus on the stereographic diagram the poles of all 24 veins appear at the center and the elongations appear as points grouped around the

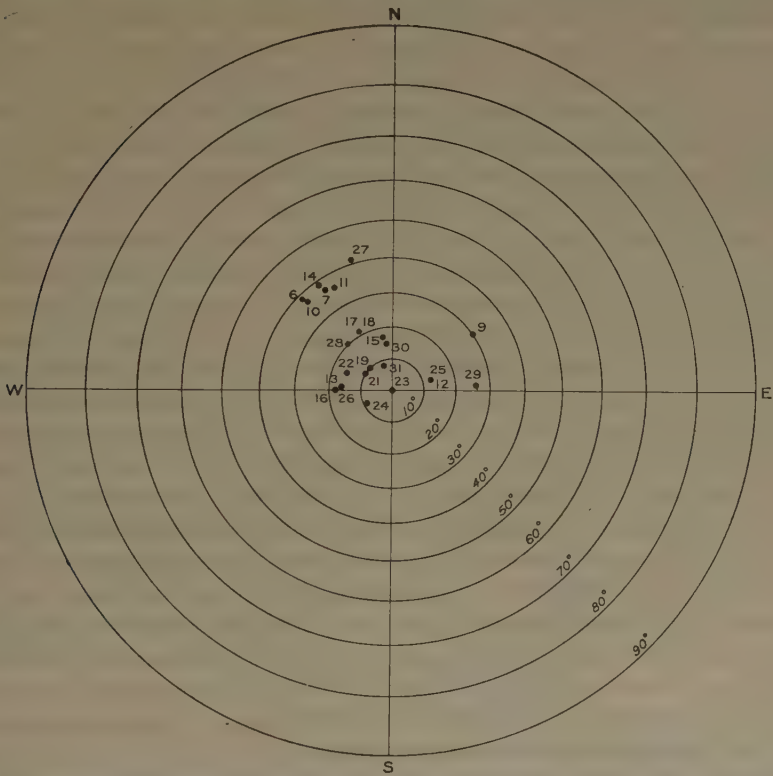

FIG. 7.—STEREOGRAPHIC PROJECTION SHOWING RELATIONSHIP BETWEEN MINERAL ELONGATION IN WALL ROCKS AND VEINS IN ELK CITY DISTRICT.

VEINS

6 Colonel Sellers
7 Buster
9 Madre d'Oro
10 Alamance
11 Old Lemroe
12 Mascot
13 Black Pine
14 Mother Lode
15 Hope
16 Blue Ribbon
17 American Eagle
18 Altemont
19 Uncle Sam
21 Hercules
22 Alberta
23 Vein a mile east of Madre d'Oro
24 Rand No. 2
25 Rand No. 3
26 Whittaker
27 Snowstorm
28 Vein a mile southeast of Blue Ribbon
29 Vein ½ mile southeast of American Eagle
30 Vein a mile southeast of American Eagle
31 Pasadena

center at angular distances from it represented by the concentric circles. The orientation of each of the 24 parts of the diagram was fixed by referring it to the strike of that vein.

The possible variations in the results due to each of the above-mentioned variable factors have been roughly evaluated in order to

approximate the expectable variations from the Cloos relationship under the assumption that the veins occupy Q points.

The attitudes of 18 of the 24 veins were measured by the writers, whereas the attitudes of the remaining 6 are from the literature or from other sources. These measurements are of several orders of accuracy, depending chiefly on the exposed extent of the vein either on the surface or underground. Furthermore, absolute accuracy is not attained in making ordinary structural observations. Perhaps 5° is a fair estimate of possible observational error as regards both strike and dip readings. Many factors necessarily affect this figure. There appears to be no way of estimating the accuracy of observations taken by others, except that where such data were used in the construction of the stereographic diagram the distribution of the projected points is about the same as those measured by the authors, and therefore such indirect data are probably of about the same degree of accuracy as those of the latter.

In order to compare the relationship between a vein and the mineral elongation it is, of course, necessary to arrive at values for the strike and pitch of the elongation at the place where the observations on the vein were made. In many cases it was not possible to get readings on mineral elongation at the place where observations were made on the vein, therefore considerable interpolation and extrapolation from points where readings were taken was necessary. In the northern and central parts of the district most of the interpolations necessary to get figures for the elongation at any vein were over distances of ½ mile or less. In the southern part, a mile appears to be a better figure, and some extrapolations were over even greater distances. The recorded elongation observations show that observations ½ mile apart may differ by 10° in either strike or dip, rarely more, and that this difference is not greatly increased even where observations are several miles apart.

There is abundant evidence in the mines to show that post-vein faulting has been active in the district. Exposures in the mines permit a crude estimate as to what effect such movements might be expected to have on concealing the relationship that has been described. As has been said before, cross faults were observed in some of the mines, notably the Blue Ribbon and the American Eagle. The Buster vein is reported to be cut off by a flat-dipping fault on the 370-ft. level. Evidence of post-vein movements essentially parallel to the veins was seen in most of the mines. A portion of the Black Pine mine serves to illustrate this point (Fig. 3). It seems quite possible that these movements are responsible in part at least for the lenticular shape of the vein, as the vein appears to taper where the strike of the fault changes. Although a good average attitude can be measured on the part of the vein shown in Fig. 3, it is clear that results differing by more than 20° might be obtained if measurements were made, for example, on two small prospect pits at

different places on the same vein, so that one observation, which is all we have on many of the veins of the district, may be expected to be in error up to at least 20°.

Therefore, if it is assumed that all of these errors have acted at a maximum and all in the same direction, a variation of 35° in strike and 35° in dip might be expected in the result obtained for any particular vein. This would give a deviation of 48° for the pole of the vein from the position occupied by the elongation.

All of the 24 mineral elongation projections lie within 41° of the projected poles, 18 lie within 30°, 13 within 20°, and 5 within 10°. Furthermore, 19 of the 24 projections lie in the northwest quadrant of the diagram, and as most of the veins trend northeast it follows that the variation is systematic in that most of the veins have somewhat steeper dips than they would have if the relationship were a true right-angle one. Thus, although at first glance the differences may seem large enough to nullify any conception of a right-angle relationship, the foregoing analysis of the errors that must have affected the results shows that the differences are not as great as might be expected.

The evidence appears to show that a relationship actually exists, for the differences between theoretical and actual figures are no greater than the differences the errors might be expected to introduce. The fact that the differences are in most cases in one direction—that the veins dip more steeply than theoretically they should, according to Cloos—seems to show that some angle other than a right angle would be a better one to express the relationship. For the veins studied this angle is about 70°.

Economic Considerations

The most productive veins in the Elk City district have been found within a belt about 2 miles wide, which follows the granodiorite contact, and it seems likely that in the future most of the productive veins may be found within this belt.

The veins do not in general have conspicuous outcrops, and an understanding of the structural pattern of the vein systems will aid in prospecting, especially where there is some doubt about the trend of a vein. All of the known productive veins are at nearly right angles to the mineral elongation, and since the strike of the foliation and the elongation in the Elk City district are not greatly different, the strikes of the principal veins are almost at right angles to the strikes of the foliation. Hence, in general, the more productive veins can be expected to strike across the foliation (schistosity) at nearly a right angle. No veins of commercial value are known to parallel the foliation of the country rock in the Elk City district. Some prospecting has been done on some of the quartzite lenses, and it is true that some of these do resemble vein quartz, but they parallel the strike of the foliation and have not been proved to contain gold in commercial quantity.

A conception commonly accepted in the district is that certain veins with similar strikes, although a considerable distance apart, are on the same fissure. This is a rather natural assumption, as illustrated, for example, by the Black Pine and Mascot mines. It is not possible to trace either vein readily on the surface for more than several hundred feet, and it is quite natural to assume that the space between them is either barren of quartz or covered with mantle rock. A clear idea of the true relationships can be gained only when the attitudes of the various veins are plotted in their proper positions in relation to the regional structure.

Cross joints of the type described by Cloos as *Q* joints would be expected to be fairly continuous both horizontally and vertically. This expectation, however, does not imply that the quartz in a vein is as continuous as the fissure that it occupies, because openings in several of the mines demonstrate that fracturing continues beyond the terminations of bodies of quartz, and that even within the lengths of some mine workings there are barren stretches between quartz lenses. It has been pointed out that part of the lenticular form probably is due to strike faulting subsequent to the introduction of quartz, but it is believed that quartz originally was introduced only along the more open parts of the fractures. In either case, it follows that a spot barren of quartz in an otherwise valuable vein should not discourage prospecting for a reasonable distance along the strike, especially if the vein structure (fissure) is well defined.

After the quartz was introduced it was considerably fractured before sulfides and gold were introduced. Some sulfides and gold were found throughout most of the quartz but they have tended to concentrate along zones of more intense fracturing to form shoots. Only the higher grade shoots were formerly worked, owing largely to excessive costs resulting from expensive transportation. New transportation facilities and more efficient metallurgical processes should make possible the working in some of the mines of much of the vein material outside of the richer shoots.

Insufficient accessible underground openings and lack of assays prohibit reliable tonnage estimates. A fact worthy of note, however, is the mineralogical similarity of all of the ore examined. This warrants consideration of the possibility of treating ore from several near-by veins in one plant.

Summary

Banded gneiss is the most abundant rock in the Elk City district of north-central Idaho. It is interbedded with schist and quartzite and in some places these rocks have been intruded by sills and dikes. Irregular bodies of augen gneiss lie transverse to the trend of the banded gneiss and schist. Granodiorite crops out over a large area and extends beyond

the limits of the district. Most of the veins lie within two miles of the gradational contact between the granodiorite and the older gneiss and schist.

The gold-bearing quartz veins of the district stand nearly at right angles to a linear elongation of minerals in the country rocks. This linear element is to be distinguished from the more commonly recognized schistosity or planar foliation of gneissic and schistose rocks.

The right-angle relationship between the veins and the mineral elongation appears to be genetic because the measured orientations of the veins do not differ from a position at right angles to the elongation by more than might be expected, considering the errors inherent in the data used. Furthermore, the departures from a 90° relationship appear to be systematic, as most of the veins dip somewhat more steeply than they would if they were exactly normal to the mineral elongation.

Hans Cloos and others have shown that a right-angle relationship exists between a linear element, called "stretching," and a set of *Q* or cross joints in certain igneous rock masses. The same phenomenon has also been observed in metamorphic rocks. According to Cloos and his associates the stretching is a result of mineral orientation during flow, and the *Q* joints develop at a slightly later stage by tension at right angles to the stretching. In this paper the relationship between the veins and the mineral elongation is compared to that between the stretching and the *Q* joints, but statements concerning the origin of the fractures containing the veins are avoided because a much greater areal study will be necessary before adequate data for positive conclusions can be gathered, and also because the writers are not convinced that they necessarily form in the manner postulated by Cloos.

An understanding of the relationship between the veins and the elongation will be of economic importance as a guide to prospecting and as a factor in forming a conception of the probable extent and attitude of veins and orebodies both horizontally and in depth.

Acknowledgments

The work in the Elk City district was carried on under a cooperative agreement between the Idaho Bureau of Mines and Geology and the United States Geological Survey. Field work occupied about six weeks in the summer of 1932. The writers wish to acknowledge the able and energetic field assistance of G. D. Emigh and the courteous and helpful aid of the United States Forest Service and of many of the inhabitants of the district, particularly Mr. Reuben McGregor of Elk City, who gave freely of his time on many occasions and also permitted access to valuable records in his possession. The writers wish also to express their thanks to G. F. Loughlin and James Gilluly of the United States Geological Survey, for helpful suggestions and criticisms.

DISCUSSION

(*Sydney H. Ball presiding*)

E. F. Fitzhugh, Jr.,* Boise, Idaho (written discussion).—During the summer of 1934 I examined about a dozen of the mines and prospects in the Elk City district. The authors are to be complimented on their careful observations and study of this area, and the choice of subject matter in their descriptions[12] is unusually useful to the field man.

The only strike faulting along a vein that I observed, which, in my opinion, should be classed as subsequent to the introduction of vein quartz was at the Blue Ribbon. Here, adjacent to a post-mineral cross fault there has been some minor movement in the plane of the vein. This dies out within a distance of less than 50 ft. from the cross fault, suggesting that it is contemporaneous and sympathetic to the transverse movement. As with the great majority of the veins, fault gouge is encountered along one or both walls. The movements that developed this gouge, however, appear to have terminated before the deposition of the vein quartz. The evidence on which I base this assumption is especially well defined in the American Eagle and Brown Bear workings; unfortunately, I have not visited the Black Pine. Throughout the district vein quartz and sulfides that have suffered from attrition are noticeably absent from the gouge of the strike faults. Moreover, the ends of the quartz lenses are often thin and attenuated. With a foot or more of gouge and finely brecciated wall rock on either or both sides of these tongues of friable quartz—which frequently are only an inch or two thick—it would appear that any later movement, if only of a few feet displacement, would have disrupted the continuity of the quartz. I am inclined to believe, therefore, that strike faulting subsequent to the introduction of the quartz was quite limited, and that the lenticular shape of the quartz bodies should be attributed to differences of permeability that existed within the fissures at the time of deposition.

The authors refer to the andesite dikes as a single group, and they suggest that these dikes may all be connected with Miocene igneous activity. This inclusive grouping is not in accord with certain field observations. The dark colored dikes at the American Eagle, for example, apparently are not displaced by the faulting along the vein, and one of these dikes crosses the vein without displacing its continuation. The obvious inference is that these dark dikes were intruded after the introduction of the quartz. At the Blue Ribbon, however, light gray porphyry dikes appear to have been present before the quartz was deposited. Wherever the porphyry is found in close proximity to the vein, it has suffered appreciable hydrothermal alteration. Conversely, where 3 or 4 ft. of solid banded gneiss separate the porphyry from the vein, the intrusive is relatively fresh. The alteration would appear to have been brought about by the magmatic solutions that deposited the quartz. Structural details indicate that the Blue Ribbon porphyry was intruded near the close of the pre-quartz faulting, and that most of the dikes entered the fault planes. Minor movement after the consolidation of the porphyry opened channelways that received the vein-quartz mineralization.

The porphyry dike that forms the footwall of the Brown Bear vein is also considerably altered, which may imply that its intrusion preceded the period of hydro-

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* Mining Geologist.

[12] See also P. J. Shenon and J. C. Reed: Geology and Ore Deposits of the Elk City, Orogrande, Buffalo Hump, and Tenmile Districts, Idaho County, Idaho. U.S. Geol. Survey *Circular* 9 (1934).

thermal vein filling. Striations caused by movement in the plane of the vein are prominent on the porphyry wall. Consequently the dike was present before the close of faulting. If the movement is accepted as prior to the deposition of vein quartz, the intrusion of the porphyry took place at an even earlier time.

It is suggested that there were two periods of dike intrusion. The first group, comprising the light colored dikes, which appear to be the more highly altered, may be a differentiate of the granodiorite. If so, they were intruded some time after the invasion of their parent magma and after the close of regional metamorphism. The entrance of these dikes, however, was prior to the deposition of the quartz veins. The later group of darker colored dikes may be of Miocene age.

An alternate possibility is that all of the dikes, and the quartz-vein mineralization as well, were connected with successive periods of Miocene igneous activity. The granodiorite intrusion almost surely influenced the structural setting of the veins, but the visible faulting on Q-joints and the subsequent introduction of silica and metallics took place when stresses and temperatures were no longer sufficient to cause metamorphism. The interval that elapsed between the development of the regional structure and the deposition of the vein quartz is unknown. Thus the quartz may be derived from the later magmas. The authors' petrographic studies may be of broad enough scope to elucidate these problems.

The relationship between elongation and the veins is clearly pointed out by the authors. As an aid to prospecting and mine development, however, the importance of this relationship depends much on the manner in which the Q-joints form. Conditions in the region vary somewhat from those postulated for the Cloos theory. So, before the economic significance of the mineral elongation can be fully explained, further study of the area and more mine development will be necessary. It is to be hoped that this structural relationship will receive adequate consideration in the future, and that its full meaning may be ascertained.

P. J. Shenon and J. C. Reed (written discussion*).—The writers stated (p. 172) that two types of faults displace the veins in the Elk City district, strike faults and cross faults. Cross faults displace veins at the American Eagle and Blue Ribbon mines more than 100 ft. and in practically all of the mines in the Elk City and adjacent districts the vein quartz is separated from the wall rocks by gouge that the writers believe was formed by movements parallel to the veins after their formation. In many mines the movements that formed the gouge apparently were not great, as the vein quartz is not noticeably fractured whereas in other mines the quartz is greatly fractured and broken. In the two drifts near the end of the mill level at the American Eagle mine the quartz was greatly shattered and could be pulled down with a prospect pick. The writers pointed out that sulfide minerals and gold occur along fractures in vein quartz. These fractures must have been formed by movements after the quartz was a solid mass. Striations and slickensiding on the vein quartz in practically all of the mines likewise attests to fault movements after the quartz was solid. Hence the writers cannot subscribe to Mr. Fitzhugh's suggestion that the movements terminated before the deposition of the vein quartz.

Mr. Fitzhugh has noted the lenslike shape of the vein quartz and, like the writers, believes that the lenticular shape was largely developed because the quartz was originally introduced only along the more open parts of the fractures (reference of footnote 12, p. 24).

Mr. Fitzhugh states that the grouping of the andesite dikes is not in accord with certain field observations. In 1932 the relationships between the dikes and the vein quartz was not well displayed in most of the mines. In 1934, when Mr. Fitzhugh

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* Published by Permission of the Director of the U.S. Geological Survey.

examined the mines, the underground openings may have offered better exposures. The writers agree with Mr. Fitzhugh that the dark colored dike on the mill level of the American Eagle mine crosses the vein quartz but to them the relationship between the cross faults and the dike was not clear (reference of footnote 12, p. 36). There is a suggestion that the dike is offset by a cross fault, as dark colored dike rock is exposed on the north side of the fault in the southeast drift of the mill level in about the position an offset segment should be found (reference of footnote 12, Fig. 4). In the Blue Ribbon mine a highly altered dike parallels the vein. Its relationship to the vein quartz was not evident in 1932. Both dike and vein, however, are obviously offset by a cross fault. Microscopically the dikes at the American Eagle and Blue Ribbon mines appear to be similar except for the degree of alteration. Both rocks are altered but the one from the Blue Ribbon is considerably more altered than the one from the American Eagle. However, it should be pointed out that the Blue Ribbon tunnel is just a few feet below the surface and the sulfides in the vein are almost entirely oxidized, so that more alteration would be expected in the dike next to the vein. To the writers the evidence at the Blue Ribbon mine did not indicate, as it did to Mr. Fitzhugh, that minor movements *after consolidation of the porphyry* opened channelways that received the vein mineralization. Mr. Fitzhugh states in another place that the dike at the Brown Bear mine was present before the close of the faulting and points to the striations along the dike as evidence of movement. He states further that if the movement is accepted as prior to the deposition of the vein quartz, the intrusion of the porphyry took place at an even earlier time. The writers observed the striation on the dike at the Brown Bear (reference of footnote 12, p. 38) but also noted that the vein matter was brecciated and therefore cannot agree with Mr. Fitzhugh that the movement was prior to the deposition of the vein quartz.

Mr. Fitzhugh suggests that there may be two periods of dike intrusions in the Elk City district; the more altered light colored ones, which may be differentiates of the granodiorite (Idaho batholith), and the darker colored dikes, which may be of Miocene age. In this respect, however, the similarity of the dikes associated with the veins, except for their degree of alteration, should be pointed out. Mr. Fitzhugh suggests an alternate possibility that all of the dikes, and the quartz-vein mineralization as well, were connected with successive periods of Miocene activity. However, the quartz veins are truncated by an erosion surface upon which sediments of probable Miocene age have been deposited.

The Central Mining District, New Mexico

By Harrison Schmitt,* Member A.I.M.E.

(New York Meeting, February, 1933)

Since the U. S. Geological Survey published the data on the Central Mining District collected by Lindgren and Graton[1] and by Paige[2] much new information has been obtained by development and mapping, but none of it had been published until recently when Kniffin[3] published on Fierro, Lasky[4] on the Ground Hog mine, Thorne[5] on Santa Rita and Landon[6] filed a thesis on the Fierro-Hanover-Santa Rita area at the University of Chicago.

During the years 1927–1930 much of the writer's time was spent in mapping the geology and ore deposits of this district, particularly in the area of the zinc deposits at Hanover. Some of the data collected are presented here. Previous publications have been freely drawn upon and additional data used that were generously supplied by L. M. Kniffin, Wilfred Wright and Gerald Ballmer. Thanks are due Augustus Locke, Samuel G. Lasky, Kniffin, Wright and Ballmer for suggestions and critical readings of the manuscript, and to the Empire Zinc Co. (a subsidiary of the New Jersey Zinc Co.) for the privilege of publishing material compiled largely at its expense.

The relation of the Central or the Santa Rita-Hanover-Fierro district to the Silver City district is shown on Paige's geologic map in the Silver City folio.[7] Granodiorite porphyry and quartz-monzonite porphyry

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[1] W. Lindgren, L. C. Graton and C. H. Gordon: The Ore Deposits of New Mexico. U. S. Geol. Survey *Prof. Paper* 68 (1910).

[2] S. Paige: Silver City Folio No. 199. U. S. Geol. Survey (1916).

[3] L. M. Kniffin: Mining and Engineering Methods and Costs of the Hanover Bessemer Iron and Copper Co., Fierro, New Mexico. U. S. Bur. Mines *Inf. Circ.* 6361 (1930) 2–5.

[4] S. G. Lasky: Geology and Ore deposits of the Ground Hog Mine, Central District, Grant County, New Mexico. New Mexico School of Mines *Circ.* 2 (1930).

[5] H. A. Thorne: Mining Practice at the Chino Mines, Nevada Consolidated Copper Co., Santa Rita, New Mexico. U. S. Bur. Mines *Inf. Circ.* 6412 (1931) 1–8.

[6] R. E. Landon: Metamorphism and Ore Deposition in the Santa Rita-Hanover-Fierro Area, New Mexico. A Study of Igneous Metamorphism. Univ. of Chicago, June, 1929.

[7] Reference of footnote 2.

"stocks," with which are associated all the important ore deposits of the Silver City district, are grouped around a structural basin or syncline 15 miles in diameter. Rocks that are as young as the Colorado of the Upper Cretaceous outcrop in the interior; and others as old as pre-Cambrian outcrop on the edge. The middle is depressed about 3000 ft. below the western, southern and eastern edges. As one travels clockwise around the outside the mining camps are encountered in the following order: Fierro, Hanover, Santa Rita, Ground Hog, Lone Mountain, Silver City, Chloride Flats, Cleveland and Pinos Altos.

Sedimentary Rocks

The sedimentary rock succession is given in the accompanying geological column.

Sedimentary Rock Succession

Age	Local Name	Composition	Thickness, Ft.	Measured by
Quaternary		Sand and gravel		
	Unconformity			
Tertiary		Gravel, sand and tuff	±300	Paige (ref. 2)
	Unconformity			
Lower Upper Cretaceous	Colorado formation	Shale, sandstone and limestone	±2000	Paige (ref. 2)
Upper Comanchean and Colorado	Beartooth quartzite	Quartzite	±100	Schmitt
	Unconformity			
Lower Permian (?)	Abo (?) Fm[a]	Red shale, 90 % and limestone conglomerate 10 %	0–100	Schmitt
	Unconformity			
Pennsylvanian	Upper Magdalena formation (261-ft. Humboldt formation at top, 130-ft. Mountain Home Shale at base)[b]	Shale 60 %; limestone, 40 %	391	Schmitt
Pennsylvanian	Lower Magdalena limestone (18-ft. Parting shale at base)	Limestone, 90 %; shale, 10 %	457	Schmitt
	Unconformity			
Lower Mississippian	Lake Valley limestone (110-ft. Hanover limestone at top)[c]	Limestone	343	Schmitt
Upper Devonian	Percha shale	Shale	±200	Schmitt
	Unconformity			
Silurian Ordovician	Fusselman and Montoya limestones	Limestone (Mg)	225	Landon (ref. 6)
Ordovician and Upper Cambrian (?).	El Paso limestone	Limestone (Mg)	500	Landon (ref. 6)
Upper Cambrian	Bliss sandstone	Limestone (Mg), shale, quartzite, conglomerate	145	Landon (ref. 6)
	Unconformity			
Pre-Cambrian		Schist		

[a] The presence of this formation was called to the writer's attention by A. C. Spencer, U. S. Geological Survey.

[b] Upper Magdalena formation and Lower Magdalena limestone are names provisionally assigned to the upper and lower sections of the Pennsylvanian by A. C. Spencer. For convenience in mapping, the names Humboldt formation, Mountain Home shale, Parting shale, Hanover limestone and others were provisionally assigned by the writer to still smaller divisions of the Pennsylvanian and Mississippian. The Geological Survey will probably rename the formations in a report that is being prepared by A. C. Spencer.

[c] Because of the deformation by the centrifugal peripheral thrust during the intrusion of the Hanover "stock" (p. 191) the Hanover limestone varies from 80 to 150 ft. in thickness, the maximum measurement having been made at the crest and the minimum on a limb of the peripheral anticline (Fig. 1). The average thickness in undisturbed areas is 110 ft. No other formations in the vicinity of Hanover are known to be greatly deformed, but at Fierro the sub-Percha limestone horizons are stretched thin by doming along their contact with the main intrusive.

Igneous Rocks

The igneous rocks are listed in the accompanying table in order from youngest to oldest:

Igneous Rocks

Age	Rock	Form
1. Tertiary................	Quartz-latite vitrophyre	Dikes
2. Tertiary................	Basalt, andesite, latite and rhyolite	Flows, tuffs and breccias; thickness, 1500+ ft.
3. Late Upper Cretaceous (?)	Quartz diorite, granodiorite and quartz-monzonite porphyries	Dikes
4. Late Upper Cretaceous (?)	Granite, granodiorite, quartz-monzonite	Stocks and/or chonoliths
5. Late Upper Cretaceous (?)	Granodiorite porphyry	Sills and laccoliths
6. Pre-Cambrian...........	Granite and pyroxenite (?)	Massive basement

The principal mineralization epoch lies between groups 2 and 3. Groups 4 and 5 appear to form a series that was intruded without interruption (p. 21) but was accompanied by minor differentiation. Several of the "stocks" when first intruded are believed to have been feeders for the laccoliths and sills (p. 21).

Areal Distribution and Structure of the Rocks

The areal distribution of the rocks is shown on Paige's map and Fig. 1. An "inlier" of pre-Tertiary sedimentary and intrusive rocks about eight miles in diameter is surrounded by volcanic rocks of Upper Cretaceous and Tertiary age and Quaternary sand and gravel. This "inlier" is a structural dome, which lies on the east limb of the larger basin or syncline previously mentioned at the beginning of the paper. "Closure" is given on the northwest side by the Barringer fault, the northwest or hanging wall of which is down 1000 ft., and on the northeast side by a normal fault at Georgetown,[8] the northeast or hanging wall of which is down an unknown, but great, distance relative to the other wall. The dome is "closed" on the south and west sides by the southward and westward dip of the sedimentary rocks.

Several secondary structural forms modify this dome: an anticline with the Fierro-Hanover granodiorite and granite "stock" as its axis, a broad flat dome which has at its center the Copper Flat quartz-monzonite porphyry[9] "stock," and a syncline that is on the same axial line as the Fierro-Hanover anticline (Fig. 1). This syncline starts just south of

[8] Reference of footnote 2.

[9] Classification by Paige. Reference of footnote 2.

FIG. 1.—PART OF AREAL GEOLOGY OF SANTA RITA SPECIAL QUADRANGLE SKETCHED FROM MAPS BY SIDNEY PAIGE (REF. 2), ALLEN PINGER, GERALD BALLMER AND HARRISON SCHMITT.

The Hanover area was plotted from maps made by Schmitt on scales varying from 1 in. = 100 ft. to 1 in. = 30 ft. The Fierro area was plotted from other maps by Schmitt: one a reconnaissance map on a scale of 1 in. = 2000 ft., and others detailed maps on a scale of 1 in. = 100 ft.

Hanover, extends southward toward the Ground Hog mine and is largely the result of faulting. Another syncline, or synclinal nose, begins near the Kneeling Nun and pitches southwestward. There is also a syncline east and one west of the Fierro-Hanover anticline.

A number of tertiary structural forms include the local dome around the Santa Rita "stock" and the tilted dome over the Fierro laccolith. An asymmetrical peripheral anticline borders the south end of the Fierro-Hanover intrusive (Fig. 1). This apparently was caused by centrifugal thrust from the main intrusive for the form of the asymmetry of the anticline and the associated thrust faults point to the intrusive as having been the source of active pressure (Fig. 4). Subsurface development showed that the Hanover limestone is thickened on the anticlinal axis and thinned on the limbs and that at one place at least the beds below the Percha shale are not folded. The main intrusive probably has a "floor" (p. 6) and evidence from the deep-level development suggests that the formations above the Percha shale were pushed over the ones below it. The magnitude of thrust is known to have been about 500 ft. from evidence given by cross-sections. The Hanover limestone apparently acted as a plastic mass when subjected to the active thrust under great confining pressure. This is indicated by the shape of the deformed limestone (Fig. 4) and the character and attitude of the pattern of the intercalated chert layers. Brecciation and faulting probably were unimportant factors in the promotion of this deformation, whereas the large polysynthetically twinned calcite crystals of which the limestone is composed in the metamorphic zone seem to have been a critical factor. The ease with which such crystals can be deformed even with a knife blade is well known. These crystals originated from the recrystallization of fossils, chiefly large crinoid stems.

The limb of the peripheral anticline nearest the main intrusive appears to have been further thinned by stretching caused by subsidence, which followed the solidification of the intrusive. That the areas including and locally surrounding most of the stocklike masses of intrusive have subsided since the magmas solidified is shown by the inward-dipping normal faults that follow the intrusive contacts, and by the occurrence of normal-fault block subsidence in areas underlain by masses of intrusive. Some of the normal faults that mark this subsidence cut the Fierro-Hanover main intrusive and also localize pre-pyrometasomatism dikes (p. 7).

Several of the major faults were mentioned above, but other important ones include the Ground Hog-Peru mines vein-fault zone, the Paige fault and the Black Hawk-Gold Gulch fault zone. The majority of the faults trend northeastward, but some trend northward. The major faulting seems to have begun in post-diorite-sill, pre-granodiorite intrusive time and continued, although decreasing in intensity, until post-ore time. The post-ore faults show relatively small offsets. Many of the faults were

reopened a number of times throughout the period ranging from pre-early-dike, pre-ore, to post-ore time.

The igneous rock structural features include the Fierro-Hanover, Santa Rita and Copper Flat "stocks," the Fierro and Fort Bayard-Santa Rita laccoliths and numerous sills. The Fierro laccolith is just west of Union Hill in the Percha shale. The Fort Bayard-Santa Rita laccolith or intrusive sheet extends from the Kneeling Nun to about the middle of the Fort Bayard reservation and is intruded near the base of the Colorado formation.

The Hanover-Fierro and Santa Rita "stocks" are granodiorite except that a certain facies of the Hanover-Fierro "stock" is normal granite.[10] The laccoliths and sills are granodiorite porphyry with the laccoliths coarser grained than the sills. The granodiorite magma seems to have had the habit of "silling" in this area and since the explored west contact of the south section (Fig. 1) of the Fierro-Hanover "stock" dips flatly inward (Fig. 4) it seems possible that this and the other "stocks" of the area have floors. Additional evidence of a "floor" at Hanover is the fact that only the super-Percha formations seem to have been thrust outward. Many of the so-called stocks in western United States are roughly cone-shaped with the point of the cone downward.

Most of the many dikes that traverse the district trend northeastward like the faults; a few trend northward, and many are located along important faults. They range from quartz-diorite porphyry to quartz-latite vitrophyre. North and south of the area of sedimentary rocks Tertiary volcanic flows, tuffs and gravels lie unconformably on the sedimentary, metamorphic and most of the intrusive rocks.

Hypogene Mineralization

At Hanover, and so far as is known everywhere else in the district, the hypogene mineralization came after the intrusion of the earliest dikes (group 3, p. 189) but before the Tertiary volcanic rocks were deposited. A stage of iron-silicon emplacement was succeeded by less abundant sulfide deposition and there is no evidence of any important depositional break from the first iron-silicon material to the last sulfide (Fig. 2). Where quantitative studies were made it was found that the pyrometasomatism caused no measurable volume change, for the thickness of the limestone and shale beds is the same whether replaced by pyrometasomatic minerals or not. The thicknesses of the beds were obtained from maps[11] that were compiled on scales varying from 1 in. = 100 ft. to 1 in. = 30 ft., and were checked by numerous diamond-drill holes. The bed contacts in the silicate zone are accurately known because of the sharp

[10] A. Pinger: Report to Empire Zinc Co. on petrography at Hanover, N. M., 1923.

[11] For methods of mapping and section measurement used at Hanover, see H. Schmitt: Cartography for Mining Geology. *Econ. Geol.* (1932) **27**, 716–36.

bed selection by the minerals (p. 205). Iron and silicon in magnetite, hedenbergite, andradite and epidote replaced Carboniferous shale and limestones, which average about 20 per cent SiO_2, and CO or CO_2 was driven off. Theoretically andradite will replace limestone containing 20 per cent SiO_2 with loss of CO or CO_2 only. The insignificant amounts of contemporaneous hypogene calcium carbonate that occur in the country and veins surrounding the pyrometasomatic deposits tend to verify the belief that not much of this compound was lost when the limestone was replaced by the pyrometasomatic minerals.

The earliest dikes at Hanover—some of which cut the main intrusive (p. 208)—are known to be pre-pyrometasomatism, for silicates and ore are localized along their contacts, epidote and minor garnet replace them, and no garnet or ore breccia has been found within them. There seems to be little doubt that the pyrometasomatism occurred after the solidification of the part of the main intrusive now exposed.[12] It may be of interest to note that the roots and branches[13] of the sphalerite orebodies extend vertically above and below the orebodies, which shows that the mineralizing fluids moved in a vertical direction at least locally and not radially away from the main intrusive as a focus. The source for the magma that made the main intrusive, and the fluids and heat that were responsible for the pyrometasomatism, seems to have been far below the zone open to observation. As will be more fully discussed in a later paper[14] there were apparently two types and epochs of igneous metamorphism at Hanover, the older represented by the hornfelsized shales and recrystallized limestones;[15] the younger by the pyrometasomatic silicates.

The simple contact metamorphism affected a fairly regular zone varying from 1000 to 3000 ft. wide around the main intrusive contact, and apparently was not greatly influenced by fractures, faults and brecciation,

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[12] J. E. Spurr and G. H. Garrey [Ore Deposits of the Velardeña District, Mexico. *Econ. Geol.* (1908) **3,** 688–725], J. E. Spurr, G. H. Garrey and C. N. Fenner [Study of a Contact Metamorphic Deposit. The Dolores Mine at Matehuala, S. L. P., Mexico. *Econ. Geol.* (1912) **7,** 444–92], J. B. Umpleby [Geology and Ore Deposits of the Mackay Region, Idaho. U. S. Geol. Survey *Prof. Paper* 97 (1917)], A. Knopf [Geology and Ore Deposits of the Yerington District, Nevada. U. S. Geol. Survey. *Prof. Paper* 114 (1918)] and others have described cases where the pyrometasomatic silicates are younger than the solidification of the "main" intrusives.

[13] Branch is a term proposed by the writer for the hypogene "leak" or outlet path of the mineralizing fluids above an orebody.

[14] H. Schmitt: The Igneous Metamorphism at Hanover, New Mexico. In manuscript.

[15] Called simple contact metamorphism by J. Barrell [U. S. Geol. Survey *Prof. Paper* 57 (1907)]. The term contact pyrometasomatism, using pyrometasomatism as defined by Lindgren [Mineral Deposits, 781. New York, 1928. McGraw-Hill Book Co.], would probably be useful to designate metamorphism with the addition of silicate material at contact zones with the understanding that it would not be applied to the deposition of "high-temperature" silicates far removed from contact zones such as occurred at Santa Barbara, Chihuahua.

whereas the contact pyrometasomatism is restricted to an inner irregular zone averaging 600 ft. wide in the Hanover limestone and less than 200 ft. in the unfavorable horizons and is closely, even sharply, controlled by structural forms. Along certain large faults it extends as roughly tabular bodies more than 1500 ft. from the intrusive contact. The character and distribution of the simple type suggest origin from pressure and the heat and possibly other properties of rapidly infiltrated hot tenuous gases. It seems reasonable to suppose that such conditions accompanied the first intrusion of the magma when it is known to have exerted differential pressure (p. 191). But the pyrometasomatism is known to have occurred after the solidification and subsidence of the intrusive. The character and distribution of this second type of metamorphism suggests origin from hot fluids less viscous than magmas, but having appreciable surface tension. In this connection the surface that marks the sharp change from massive silicates and sulfides to limestone is suggestive. This shows rounded forms on a large scale, which are convex away from the pyrometasomatic masses. It seems unlikely that such sharp contacts and gently rounded surfaces could have resulted from deposition by fluids having no appreciable surface tension.

Suggestive, but less important, evidence for two ages of metamorphism is that the grain of the andradite varies with the grain of the recrystallized limestone (p. 205) and the garnet—since it is not extensively shattered in the peripheral anticline—formed after the Hanover limestone was deformed. Finally, veinlets of epidote cut hornfels.

No material appears to have been added during the simple contact metamorphic epoch, but, during the time of the contact pyrometasomatic, calculations show that for every cubic meter of average host rock replaced by silicates, 1000 kg. of Fe_2O_3, 300 of FeO, 600 of SiO_2 and minor amounts of metals, were added and 800 kg. of CO_2 was lost. Thus there was a net gain of more than one metric ton of material for every cubic meter of average host rock replaced.

The Fierro mineralization is largely a replacement of the dolomite and magnesian limestones that make up most of the stratigraphic section below the Percha shale. Massive serpentine, wollastonite and augite(?)[16] are the principal silicates there, not garnet and epidote. Indeed, garnet is probably less than one per cent of the silicates. Kniffin reports that comparative analyses indicate neither loss of magnesia nor gain in silica. The massive serpentine lacks evidence of having been derived from the alteration of earlier magnesian silicates. The writer believes that it is hypogene and in this connection it should be noted that serpentine was made by F. G. Wells at the University of Minnesota[17] by digesting dolomite and

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[16] Landon reports augite (?) at Fierro (reference of footnote 6).
[17] J. Gruner: Oral communication.

water glass at 300° C. In places serpentine seems to replace cherty bands in the magnesian limestone and some, it must be admitted, is the alteration product of augite (?), as reported by Landon. The massive serpentine is cut by veinlets of magnetite. Wollastonite occurs as tabular masses of fine-grained, dense, hard rock separating tabular magnetite orebodies and may be the metamorphic product of the beds of arenaceous limestone that occur in the Montoya limestone. The few remnants of Carboniferous limestone have been replaced by andradite and epidote. It is noteworthy that deep mine development in the magnesian limestones below the Percha shale at Hanover disclosed serpentine and magnetite, but no garnet. These limestones seem to differ from those above the Percha shale in no essential except magnesia, which may be as high as 20 per cent. Did the magnesium inhibit replacement by iron and silicon as andradite, epidote and hedenbergite and favor augite (?) and serpentine? But the magnetite appears to have replaced magnesian limestone and magnesia-free limestone with equal facility. Analyses of the sub-Percha limestones by J. J. Jones, chief chemist for the Nevada Consolidated Copper Co., are given in Table 1.

TABLE 1.—*Analyses of Sub-Percha Limestones*
(J. J. Jones)

Minerals	El Paso Limestone		Montoya Limestone	
	Lower Part	Upper Part	Lower Part	Upper Part
Silica, per cent	20.62	8.57	34.03	2.77
Oxides of iron, aluminum, phosphorus and titanium, per cent	7.59	3.45	3.96	1.76
Calcium oxide, per cent	31.44	37.65	19.98	29.30
Magnesium oxide, per cent	7.09	9.38	13.27	19.80
Carbon dioxide, per cent	32.51	39.60	28.67	46.01
Total	99.25	98.65	99.91	99.64

The silica-iron stage is represented in the Santa Rita area by the widespread silicification[18] of the granodiorite porphyry and the sedimentary rocks and by replacement of the limestone by garnet, magnetite, epidote and pyroxene.[19] The abundant sericitization suggests that potash was introduced.[20] Less important sericitization and silicification

[18] It is appreciated that much if not all of the silicification of the igneous rocks may be due to silica released by the replacement of feldspars by sericite. See A. C. Spencer [The Geology and Ore Deposits of Ely, Nevada. U. S. Geol. Survey. *Prof. Paper* 96 (1917)] and S. Paige: [Copper Deposits of the Tyrone District, New Mexico. U. S. Geol. Survey *Prof. Paper* 122 (1922)].

[19] Paige: Reference of footnote 2; 16, 17.

[20] References of footnote 18: Spencer, 55–59; Paige, 25–28.

occurs at Hanover and Fierro. Some manganese is found in the minerals of the silica-iron stage, particularly in the Hanover hedenbergite, which carries up to 1 per cent Mn. The veins of the Gold Gulch and the Ground Hog area (Fig. 1) contain abundant silica as quartz, but iron is scarce except in sulfides. The accompanying lists and Fig. 2 (on Hanover) summarize the paragenesis of the minerals and elements of the district and of the separate camps:

Paragenesis of Minerals and Elements

FIERRO[a]

Serpentine
Wollastonite
Garnet
Epidote
Augite (?)
Magnetite
Pyrite
Pyrrhotite
Chalcopyrite
Chalmersite
Sphalerite

SANTA RITA[b] (TENTATIVE)

Epidote
Pyroxene
Garnet
Magnetite
Orthoclase
Sericite
Quartz
Pyrite
Chalcopyrite
Pyrrhotite
Sphalerite

General order of deposition of elements in district:

Stage A

Si, Fe

Stage B

Si, Fe, Cu, Zn, Pb, S, K, Mn, Au, Ag

[a] Most of these data are from Landon (reference of footnote 6) and G. M. Schwartz [Chalmersite at Fierro, New Mexico. *Econ. Geol.* (1923) **18,** 270–77.]

[b] Data from papers by Paige and Landon (references of footnotes 2 and 6).

SUPERGENE MINERALIZATION

Fierro.—Some of the near-surface magnetite was oxidized to martite and the accompanying sulfides desulfurized. These changes improved much of the iron ore, for sulfur is a deleterious impurity in the deeper unoxidized ore.

Hanover.—Some near-surface sphalerite—much of it originally low-grade ore (± 7 per cent Zn)—was oxidized, dissolved and precipitated in adjacent limestone as rich (± 30 per cent Zn) calamine-smithsonite ore.

Santa Rita.—The supergene effects at Santa Rita seem to be those of normal enrichment.[21] Pyrite, containing microscopic chalcopyrite, has been enriched from 0.2 to 0.4 to 1.5 per cent Cu by the formation of supergene chalcocite. The enriched sulfide zone is 350 to 400 ft. thick

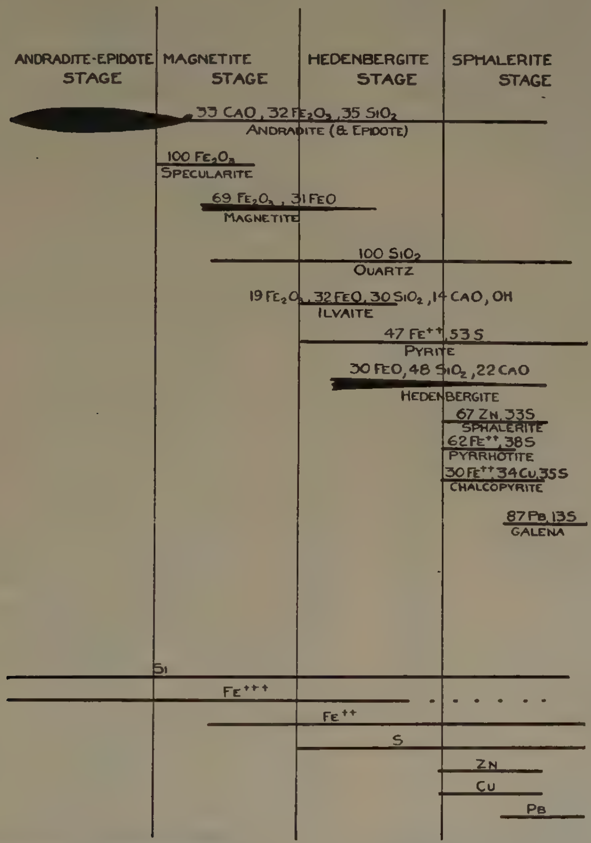

FIG. 2.—DIAGRAM OF PARAGENESIS OF MINERALS AND ELEMENTS AT HANOVER, N. M., BASED ON MACROSCOPIC AND MICROSCOPIC STUDIES.

and its lower contact is an uneven surface below which one prong extends about 500 ft. The ground water originally stood at the top of the enriched zone, which is also the bottom of a leached capping about 100 ft. thick. Kaolin and iron oxides are abundant. Paige notes that from the surface downward the succession of copper minerals is: carbonates, oxides, native copper and chalcocite. The carbonates descend below 300 ft. and native copper has been found at 1020 feet.

[21] Paige: Reference of footnote 2; 17.

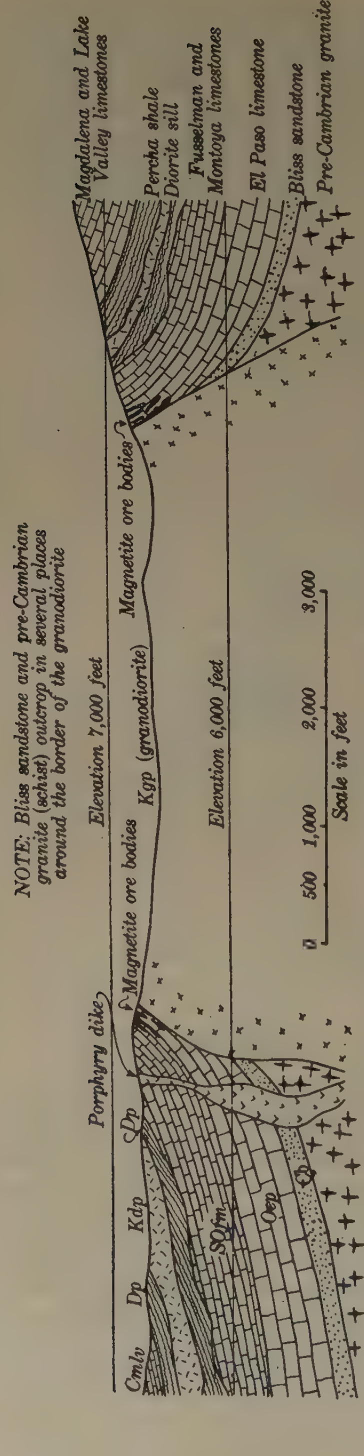

Fig. 3.—Geologic section through main intrusive, Fierro, N. M. By Lloyd M. Kniffin. Reprinted from U. S. Bureau of Mines *Information Circular* 6412.

Form and Localization of the Metallization

Fierro.—The orebodies at Fierro (Figs. 1 and 3) were localized in a predominating degree by the intrusive contact, although faults, dikes and bedding had some effect. At the shallow depth now developed, not much over 200 ft., the dip of the intrusive contact and the beds is the same, as nearly as can be estimated (Fig. 3). The orebodies follow the intrusive contact and replace favorable beds, giving, as a result, tabular bodies, which average 25 ft. in thickness, separated by tabular horses of wollastonite rock. The augite (?) is seldom more than 50 ft. from the intrusive contact, and the more abundant serpentine, although usually near magnetite, favors the outer contact of the magnetite-silicate zone, which is seldom more than 200 ft. wide. Besides occurring along the main contact, magnetite is found at places along the Barringer fault and at sill contacts, or replaces favorable beds in thin layers at least 2000 ft. away from the main contact. It is found along a dike in the Union Hill country.

A copper deposit that resembles the disseminated ore of Santa Rita is found at Hanover Mountain (Fig. 1) in the hanging wall of the Barringer fault. The country rock is Colorado shale and sandstone and the mineralization is hypogene quartz-sericite-cupriferous-pyrite with

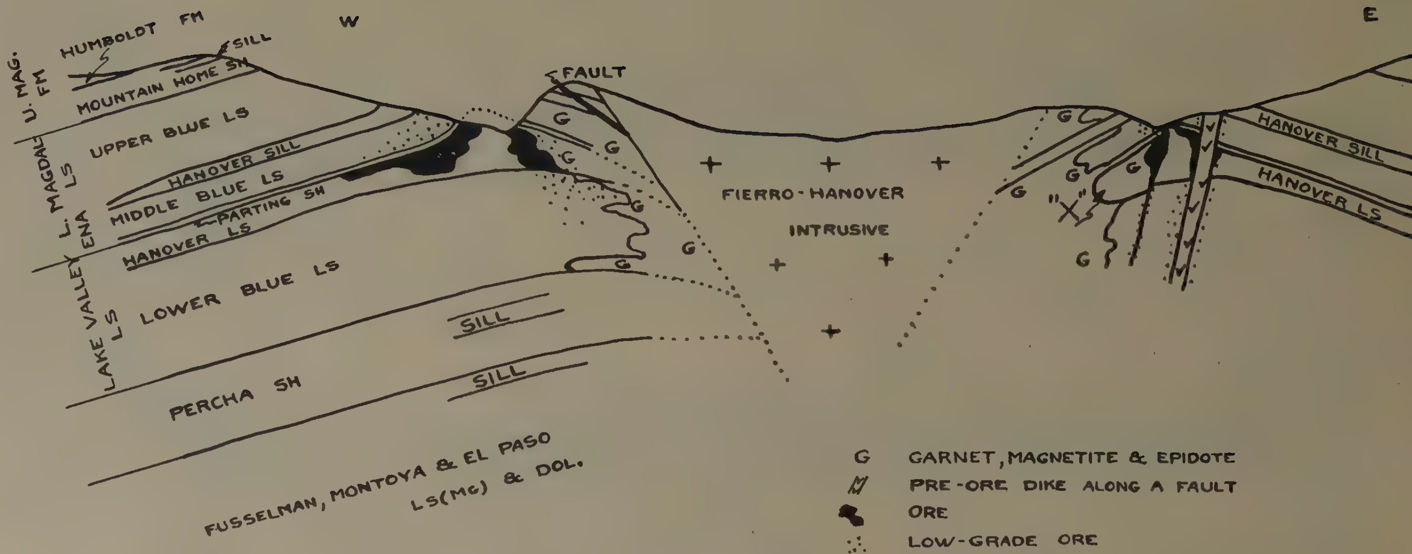

Fig. 4.—Simplified diagrammatic sketch representing a west-east vertical section through the Hanover area. Not drawn to scale. The western half represents the conditions closely, the eastern half is a diagrammatic composite of several sections on the south and east sides of the main intrusive made to illustrate several conditions not all shown on any one original section. The condition shown at *X*, where the Hanover limestone is drawn as though squeezed out, is found on the south side of the main intrusive, where it seems to have been the effect of the tendency of the Hanover limestone to undergo plastic flow when subjected to great unbalanced pressure.

chalcocite enrichment. Brecciation of the hanging wall of the fault was apparently responsible for the localization of the hypogene mineralization as well as the supergene enrichment. The "preparation" of the ground was not as thorough as at Santa Rita, the deposit is much smaller, and the ore extracted was largely from fissures.

Hanover Mines.[22]—There is a definite structural control for most of the zinc orebodies at Hanover. Most of the ore is in the 110-ft. crinoidal Hanover limestone bed at the top of the Mississippian, commonly spreads out under the superjacent 18-ft. Pennsylvanian Parting shale layer (Fig. 4), is always in ground that was fractured, faulted, or otherwise "prepared" in pre-mineralization time, and is closely associated with earlier silicate mineralization. Some of the largest orebodies lie along a faulted garnet-limestone contact corresponding to the outer edge of the garnet zone (Figs. 4 and 5). Horizontal blanket-like orebodies associated with gently flexed anticlines and synclines occur just under the 18-ft. shale layer. They vary from 1 to 45 ft. in thickness and up to 200 ft. in diameter. The fault-dikes yield steep veinlike, tabular orebodies with a maximum width of 30 ft., height of 110 ft. and length of 1000 ft. Faults and fissures localize various podlike orebodies.

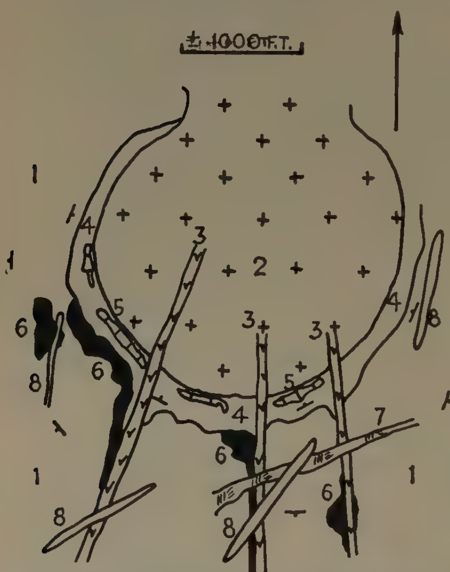

FIG. 5.—GREATLY SIMPLIFIED DIAGRAMMATIC PLAN SHOWING SURFACE GEOLOGIC RELATIONS AT HANOVER ZINC MINES.

Drawn from maps by Harrison Schmitt. Faults not shown. Not drawn to scale.

1. Mississippian and Pennsylvanian limestone and shale.
2. Granodiorite.
3. Quartz-diorite porphyry dikes.
4. Andradite zone.
5. Magnetic orebodies.
6. Sphalerite orebodies.
7. Quartz-monzonite porphyry dikes.
8. Quartz-latite vitrophyre dikes.

Santa Rita.—The ore at Santa Rita has the shape of a horseshoe 4000 ft. in diameter and 350 to 400 ft. thick with its southern limits undefined. It envelops a granodiorite "stock" (Fig. 6).

Black Hawk and Ground Hog Mines.—Although the orebodies of the Black Hawk-Ground Hog area lie in veins, they are not all tabular. The Black Hawk mine orebodies are chimneylike (Fig. 7), whereas the Ground

[22] A more complete discussion of the form and localization of the orebodies at Hanover is given in the paper beginning on page 36.

Hog orebody[23] is a faulted mass (Fig. 8) which now appears lenslike, but is not fully developed. Developed portions show a vein width up to 40 ft.

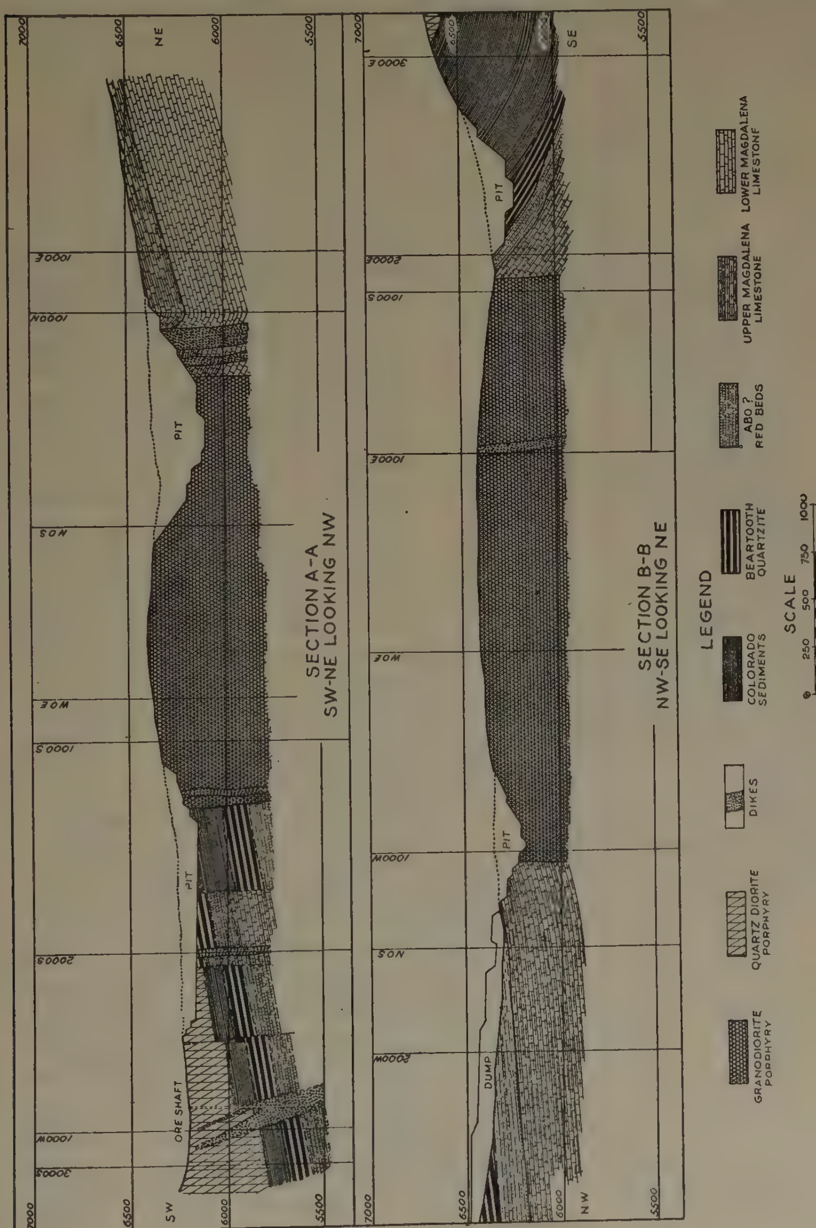

FIG. 6.—GEOLOGIC SECTIONS AT SANTA RITA, NEW MEXICO. By Gerald J. Ballmer. Reprinted from U. S. Bureau of Mines *Information Circular* 6412.

ZONING OF MINERALS

There is a distinct zoning of the introduced minerals around the Hanover-Fierro stock. Most of the magnetite, although later than the

andradite, lies adjacent to the intrusive contact; the andradite lies next outward (Fig. 5). This relationship is explained by the fact that the garnet was brecciated along the intrusive contact before the magnetite came in. In many places the magnetite is the matrical material in a breccia of garnet and in places it veins massive garnet. Sphalerite, chalcopyrite and minor galena are found adjacent to, but on the outer side of the garnet zone (Fig. 5), although minor sphalerite occurs adjacent to magnetite in a few places where the silicate zone is narrow; as, for example, at the Republic iron mine[24] open cut at Fierro. On the Barringer fault zone magnetite and silicates predominate near the main stock, but chalcopyrite and sphalerite increase westward. No galena has been reported on the developed portion of this fault, but a mile southwest (Mountain Home mine) both lead and zinc have been mined from tributary or auxiliary faults.

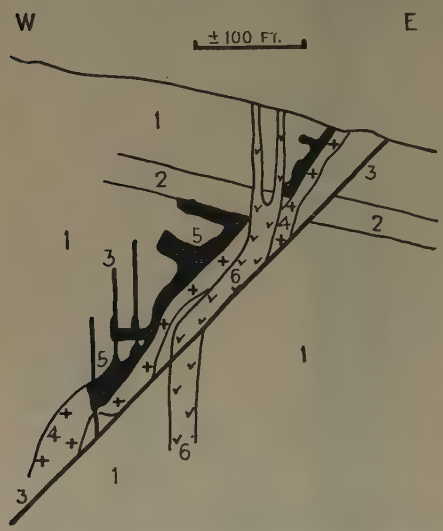

Fig. 7.—Generalized geologic section through Combination (Black Hawk) mine.

Sketched from the original by Wilfred Wright. Not drawn to scale.

1. Mississippian and Pennsylvanian limestone and shale.
2. Pennsylvanian shale.
3. Faults.
4. Pre-ore quartz-diorite porphyry dike.
5. Ore.
6. Post-ore quartz-latite vitrophyre dike.

At Hanover any given ore-bearing fault, such as the Republic mine fault zone, will show magnetite and minor sphalerite adjacent to the contact zone, and sphalerite with no magnetite and with lead less than 0.1 per cent next outward. Within 1000 ft. farther outward, the lead may increase from 0.1 to 3.0 per cent, whereas the zinc will remain constant or increase a few per cent. In detail the sphalerite orebodies, even those nearest the intrusive, which have a low average lead content, are enclosed by leady jackets (Zn, 15 per cent; Pb, 3 per cent) usually less than 5 ft. thick. The central mass of such an orebody, however, may be very high-grade zinc (55 per cent) with lead as low as 0.01 per cent. The small quantity of copper at Hanover is found in magnetite-sphalerite, sphalerite-low-lead orebodies, or in the rare pyrrhotite-sphalerite ore. A little copper occurs in the main "stock" at the U. S. Copper mine shaft.

[23] Reference of footnote 4.

[24] Different from the Republic mine a mile farther south at Hanover.

The zoning at Santa Rita is vague. On the north side of the granodiorite porphyry "stock" is a granodiorite porphyry breccia mass containing matrical orthoclase and magnetite. Magnetite and garnet occur in limestone on the north contact of the "stock" and not far from this

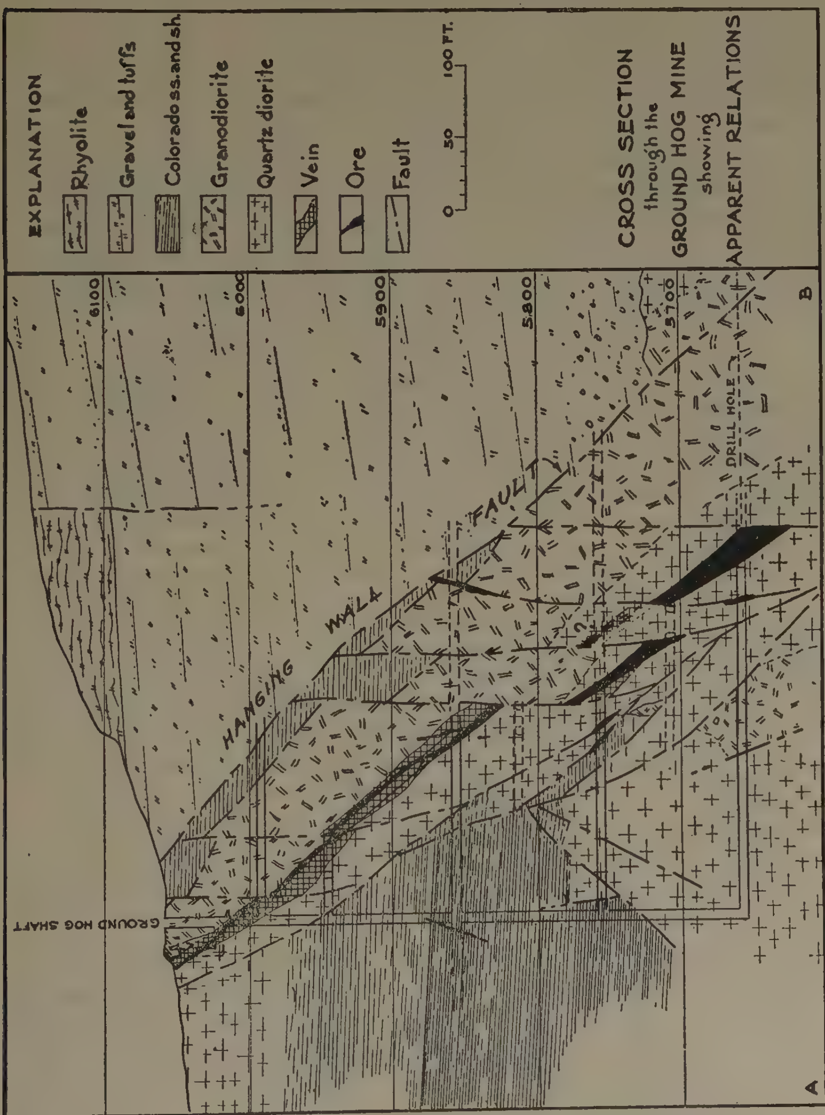

Fig. 8.—Section through Ground Hog mine showing apparent relations. By Samuel G. Lasky. Reprinted from *Circular* No. 2, New Mexico School of Mines and State Bureau of Mines and Mineral Resources.

breccia. The main mass of copper ore is found south of the breccia and a block of relatively unaltered "stock."

Silver, gold and quartz are prominent only in the mines and prospects that lie beyond the "silicate" ores. On the extreme southwest edge of

the district carbonates are found with the quartz but appear to be later than the commercial mineralization.

Variations in Relative and Absolute Concentrations of Minerals and Elements

The minerals identified to date at Fierro, Hanover and Santa Rita are listed in Table 2. Apparently the suites are closely allied. Eventually all of the minerals found at one place may be expected to be found at the others. At the Mountain Home mine (Fig. 1) vesuvianite occurs in the Abo formation and fluorite is found with the ore. Analyses of composite samples of large quantities of ore at the various mines are given in Table 3.

The difference in the quantity of a given mineral or element deposited in any area of a given type is noteworthy. Magnetite, serpentine, wollas-

Table 2.—*Minerals Identified Up to January, 1933*

Fierro	Hanover	Santa Rita
Magnetite	Magnetite	Magnetite
Pyrite	Pyrite	Pyrite
Pyrrhotite	Pyrrhotite	Pyrrhotite
Chalcopyrite	Chalcopyrite	Chalcopyrite
Sphalerite	Sphalerite	Sphalerite
Chalmersite	Specularite	Specularite
	Galena	Molybdenite
Quartz	Quartz	Quartz
Sericite	Sericite	Sericite
Garnet	Garnet	Garnet
Epidote	Epidote	Epidote
Serpentine	Serpentine	
Augite (?)	Augite (?)	
Wollastonite	Hedenbergite	
Chalcedony	Zoisite	
Tremolite	Piedmontite	
Crysotile	Ilvaite	
	Actinolite	

Table 3.—*Analyses of Composite Samples of Ore*

Fierro (Kniffin[a])	Per Cent	Hanover (Pinger[b])	Per Cent	Santa Rita (Thorne[c])	Per Cent
Fe	51.00	Fe	6.19	Fe	3.14
Cu	0.37	Zn	17.49	Cu	1.32
Mn	0.72	Mn	0.94		
CaO	1.41	CaO	8.09		
MgO	13.38	MgO	1.81		
S	0.38	S	10.19		
P	0.058	Pb	0.13		
SiO_2	7.28	CO_2	3.37		
Al_2O_3	1.42	Insol	49.77		

TABLE 3.—(*Continued*)

Betty Jo Mine (southwest part of district) (Vein mineralization)		Ground Hog (Lasky[d])	
Ag, oz	4.2	Ag, oz	8.0
Au, oz	0.01	Au, oz	0.05
Pb, per cent	18.2	Pb, per cent	8.0
Cu, per cent	1.5	Cu, per cent	4.0
Zn, per cent	17.3	Zn, per cent	16.5
S, per cent	22.1		
SiO_2, per cent	22.2		
Fe, Mn, per cent	11.0		
Al_2O_3, per cent	2.4		

[a] Reference of footnote 3.
[b] Reference of footnote 10.
[c] Reference of footnote 5.
[d] Reference of footnote 4.

tonite and augite (?) predominate at Fierro; andradite, magnetite, epidote, hedenbergite and sphalerite at Hanover; quartz, sericite, garnet and cupriferous pyrite at Santa Rita; and in the veins on the southwest side of the district, quartz, sphalerite, galena, chalcopyrite and pyrite. The variation in the composition of the wall rocks, and the former temperature decline with distance from the intrusive "stocks" doubtless contributed in causing this differentiation. But, a difference in the composition of the ore-making fluids was probably a factor also (p. 207).

Influence of Wall Rocks

The chief wall rocks at the three principal mineralized areas differ greatly. The magnesian limestones and dolomite below the Percha shale predominate at Fierro, and the nonmagnesian limestones above the Percha shale at Hanover. Still younger sedimentary rocks, and particularly a granodiorite porphyry "stock" and a granodiorite porphyry laccolith, enclose the ore at Santa Rita.

The extreme bed selection by the minerals is a feature of the Hanover geology. Andradite and hedenbergite are limited to the nonmagnesian limestone above the Percha shale. Coarse white fossiliferous limestone is replaced by coarse brown andradite and "cauliflowers" of hedenbergite up to 6 in. in diameter. Fine, impure (shaly) gray limestone is replaced by dark fine andradite and fine-grained hedenbergite. Epidote is limited to aluminous rocks such as shale beds and dikes, except in the blocks of most intense metamorphism, where it tends to wander somewhat. At least 95 per cent of the sphalerite and ilvaite is limited to the 110-ft. crinoidal Hanover limestone at the top of the Lake Valley limestone. Serpentine, wollastonite and augite (?) are found only below the Percha shale in the magnesian limestones. Magnetite is found in all horizons. Dikes and sills are appreciably replaced only by epidote, quartz, sericite, carbonates and minor garnet.

The available data are meager on the influence of the wall rocks on the mineralization at Santa Rita. Landon[25] says that the upper Magdalena formation (shale, 60 per cent and limestone, 40 per cent) is metamorphosed to garnet and quartz. He believes that residual chlorite may represent former hedenbergite and states that the Abo formation (shale with thin beds of limestone at the base) metamorphoses to magnetite and chlorite. Paige[26] notes the selective silicification of the Colorado formation and quartz-diorite porphyry, and the occurrence of garnet, epidote and pyroxene in the limestones.

Much of the disseminated copper ore occurs in the recently recognized south extension of the main granodiorite "stock" and in the adjacent granodiorite porphyry laccolith, shale and limestone. Most of the first-mined rich ore at Santa Rita was a replacement of limestone at the northeast and southeast contact of the sedimentary rocks with the granodiorite stock.

Influence of Temperature

The evidence suggests that magnetite was deposited at higher temperature than sphalerite and chalcopyrite, for most of it lies near the contacts of the granodiorite "stocks" and it is earlier than the sphalerite and chalcopyrite. Fe^{+++} appears to have become unstable under the later, cooler conditions when sulfides were being deposited (Fig. 2).

Lead-free sphalerite appears to have required a relatively high temperature for its formation because it is always found in association with minor, but contemporaneous andradite, hedenbergite and epidote—the main mass of silicates, however, was earlier (Fig. 2). The zinc-lead ores occur farthest from the zone of silicates, magnetite and lead-free sphalerite ores. They are associated with quartz, gold and silver. At the Black Hawk mine, about a mile southwest of the Hanover "stock," almost no quartz occurs, but silicates characteristic of Hanover are abundant. This indicates high temperature and accords with the low lead content, about 1.0 per cent. Zinc averages around 10.0 per cent. Farther southwest along the same zone, silicates disappear, quartz becomes abundant and lead increases.

Since the pre-ore pre-silicate dikes (group 3, p. 189) cut (Fig. 1) and so are younger than the central "stock," the question of the source of the heat that was a condition of the silicate phase arises; that is, whether the heat came from the "stock" itself or from fluids of a deeper origin. It seems doubtful that the heat after solidification from so small an intrusive could have been sufficient to raise the temperature of a contact zone 200 ft. wide high enough for garnet to form there.

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[25] Reference of footnote 6.

[26] Paige: Reference of footnote 2; 16, 17.

Magnetite and orthoclase, probably representing high temperature, lie on the north side of the granodiorite "stock" at Santa Rita. But the association of copper with quartz-sericite suggests lower temperature conditions. A quartz-sericite noncopper phase of alteration can be recognized at Hanover in the later, near-end-of-ore-time dikes and also definitely post-ore Tertiary dikes. The quartz-sericite-copper mineralization that occurs at Fierro in Hanover Mountain in the hanging wall of the Barringer fault has been mentioned. Neither magnetite nor any of the silicate minerals of Fierro that are supposed to represent high temperature are found with this ore, but these minerals with chalcopyrite occur adjacent to and in the fault.

Difference in Composition of the Mineralizing Fluids

The qualitative equivalency of the minerals and elements at the three mineralization foci, Fierro, Hanover and Santa Rita, suggests that the mineralizing fluids were closely similar. Variations in the host rocks and temperature seem to have determined the variations in the deposition of silicon, lead and most of the zinc. Iron when deposited as magnetite appears to have been dependent on temperature, but was not greatly influenced by the composition of the host rock. Copper as chalcopyrite seems to have been even more ubiquitous than the magnetite, for it is found in almost every variety of rock and type of geologic situation: as disseminations in a "stock," laccolith and the sandstone-shale hanging wall of a master fault, as ore in several "high-temperature" silicate-magnetite zones and with lead-zinc ore in the "moderate temperature" veins. The great concentration of copper at Santa Rita suggests that there was a greater charge of copper in the mineralizing fluids at that focus than at the others.

Summary—Succession of Events

In the Central district the first post-Algonkian igneous activity was the intrusion of sills, laccoliths and sheets in late Upper Cretaceous (?) time. These intrusives are spatially and petrographically related to local "stocks" (Fig. 1). The Santa Rita "stock" appears to merge into the Fort Bayard-Santa Rita laccolith or sheet and the Hanover-Fierro "stock" is difficult to separate from the Fierro laccolith at its "contact" with it. Apparently the sills and possibly the Fierro laccolith solidified before the intrusion of magma ceased in the "stocks" and were crosscut and folded with the sedimentary rocks by the final thrust of the intrusive, which was a horizontal and centrifugal thrust in the Hanover area and resulted in an asymmetrical peripheral anticline (Fig. 1) and minor thrust faults. Solidification of the magmas was succeeded by subsidence in the areas including and surrounding the Hanover-Fierro and Hanover Basin intrusives as shown by extensive normal faulting and stretching of the

beds at the intrusive contacts. Other normal faults, in many places and of many bearings, but some radiating from the intrusive and the majority bearing northeast (Fig. 1), were contemporaneous with the subsidence, cut the Fierro-Hanover intrusive and continued to post-ore and to even late Tertiary (?) time. Many of these faults localized the intrusion of the earlier dikes of group 3 (p. 189). A silicate-sulfide epoch of mineralization followed the intrusion of these dikes, and the mineralization had passed the silicate stage when the younger dikes of group 3 were intruded. These later dikes were affected by quartz-sericite alteration mainly, whereas the earlier were largely epidotized and garnetized.

The commercial mineralization was followed by deep erosion (Eocene ?) and then an epoch of Tertiary volcanism began, accompanied by the intrusion of the quartz-latite vitrophyre dikes of group 1 (p. 189) some of which cut the orebodies. Finally, erosion removed most of the volcanic rocks that lay immediately over the area described (Fig. 1).

DISCUSSION

(*Albert O. Hayes presiding*)

R. E. Landon,* Colorado Springs, Colo. (written discussion).—I have read with much interest this masterly presentation of the geology in a region of complicated relationships. There is a minor omission regarding the mineralization at Santa Rita. Sericitization preceded the introduction of magnetite, quartz and orthoclase. This would indicate a drop in temperature after which a surge occurred bringing with it higher temperatures and the deposition of orthoclase and magnetite. Orthoclase replaced sericite and filled fractures. This I have described in the *American Mineralogist* for September, 1932, under the title "Desericitization: A Process Operative During High Temperature Mineralization." I cannot say whether this early sericitization preceded or followed the epidote-pyroxene-garnet stage (p. 196) or followed it, but since magnetite is usually associated with these minerals, it would seem most likely that the sericitization came earlier. Chalmersite, mentioned on the same page, has been shown to be identical with cubanite.

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* Colorado College.

Hog Mountain Gold District, Alabama*

By C. F. Park, Jr.†

(New York Meeting, February, 1935)

Hog Mountain is in the north central part of Tallapoosa County, Alabama, about 13 miles northeast from Alexander City. The Hog Mountain Mining and Milling Co. controls 1658 acres of land and is the only company operating in the district. The principal mine workings are in sections 10 and 15, T.24N., R.22E. The region has been visited by geologists many times, has been briefly described in several papers,[1] and mentioned in many others. No detailed map of the mine or vicinity has been published.

The field work for this report was started in March, 1934, as part of the Public Works reemployment program. About a month and a half was spent mapping both the surface and underground geology.

The mine owners and operators have cooperated in every way possible to facilitate the work. N. O. Johnson, the mine engineer, E. W. Ellsworth, J. E. McCoy and J. G. Englebert have acted as assistants for part of the work. The University of Alabama and the State Geologist's office have aided materially by permitting free use of their libraries and laboratory equipment.

Geography

Hog Mountain forms a conspicuous ridge that rises to a height of a little more than 1000 ft. above sea level, and about 400 to 500 ft. above the adjacent country. The ridge is composed of granitoid intrusive rock and silicified schist that are more resistant to erosion than the surrounding softer schist. The topography of the area around the ridge is gently rolling and is typical of the subdued forms of the deeply eroded Southern

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* Published by permission of the Director of the U.S. Geological Survey. Manuscript received at the office of the Institute Oct. 25, 1934.

† U.S. Geological Survey, Washington, D.C.

[1] W. B. Phillips: The Gold Fields of Alabama. Alabama Geol. Survey *Bull.* 3 (1892) 36–55.

H. D. McCaskey: *Mineral Resources of the United States* (1908): 650–2.

H. D. McCaskey: Notes on Some Gold Deposits of Alabama. U. S. Geol. Survey *Bull.* 340 (1908) 36–52.

T. H. Aldrich, Jr.: The Treatment of the Gold Ores of Hog Mountain, Alabama. *Trans.* A.I.M.E. (1909) **39**, 578–583.

G. I. Adams: Gold Deposits of Alabama. Alabama Geol. Survey *Bull.* 40 (1930) 49–50.

Appalachian region. The country is well drained and is characterized by broadly rounded valleys or hollows and by wide flat-topped northeast trending ridges, parallel to the strike of the schistosity. The drainage from Hog Mountain and the surrounding area goes into Hillabee Creek, one of the larger branches of the Tallapoosa River.

The climate is mild and somewhat humid. The average annual rainfall is about 55 in. Thunder showers are common during the summer. A little snow may fall during the winter but melts rapidly.

The vegetation is typical of the Southern Appalachian region. Much of the hill country is covered with second growth pine and oak. Some few areas of large trees, including oak, hickory and long and short leaf pine, remain uncut. Much of the country is covered by thick underbrush. Usually once a year, commonly in the dry early spring, fires are started to clear out the underbrush. These brush fires are usually abandoned to go where they will and in places constitute a real menace to property.

General Geology

Two rock formations have been distinguished at Hog Mountain: the Wedowee formation and an intrusive quartz diorite, which is usually considered to be a small offshoot from the much larger mass of Pinckneyville granite to the west.

Wedowee Formation

The fine-grained, dark gray graphitic schists of the Wedowee formation are widely distributed near Hog Mountain. The schists are at least in part of sedimentary origin; they are, in places, partly recrystallized and contain mostly quartz, amorphous graphite and fine sericite. Some garnet and tourmaline occur locally. A bladed mineral in the schist near the quartz diorite contact may have been originally andalusite, but it is now completely altered to sericite and fine-grained quartz. Bedding planes in the schist are almost entirely obliterated, but thin bands ($\pm \frac{1}{2}$ in. thick) of quartzite were found near the south end of the intrusive mass. These thin bands are cut by the schistosity at an angle, usually about 30°.

The schist planes at Hog Mountain generally strike 10° to 20° east of north and dip steeply to the east, but they are intricately folded and faulted. Although not established conclusively, it is considered likely that representatives of the thrust faults that are known throughout this portion of Alabama occur in the immediate vicinity of Hog Mountain. Owing to the uniform character of the schists and the poor, deeply weathered exposures, it was not found possible in the available time to decipher the details of the folding and faulting.

According to Adams the formation may have a total thickness of 10,000 ft. and ranges in age from Cambrian to Carboniferous.[2] It may, however, be pre-Cambrian.

Quartz Diorite

The intrusive rock at Hog Mountain is light gray and has an even granitoid texture, the average grain size being about 2 mm. Under the microscope the rock is found to consist mainly of quartz, zoned plagioclase feldspar and biotite. Quartz is abundant but is thought to be in part of secondary origin, since near the veins the quartz content increases, and the mineral occurs in small cross-cutting stringers. Near the veins the biotite is usually altered to sericite, or in places to chlorite. Apatite, tourmaline, zircon, garnet and rutile have been identified as accessory minerals. Some sulfide, usually pyrite, and iron oxides are present in all the material examined, as are small amounts of kaolin and carbonates. In previous reports the rock has been called a granite. It is more nearly a quartz diorite and will be so called in this report.

The age of the quartz diorite is not known. Adams says:[3] "Presumably all of these areas of granite were derived from the same regional magma" [Pinckneyville granite]. The age of the Pinckneyville granite has generally been considered to be post-Carboniferous. It was certainly intruded after most of the deformation that formed the Wedowee schists had taken place.

Structure.—The quartz diorite occupies an area about 4800 ft. long and 800 to 1300 ft. wide. The strike of the long axis of this body is about N.10E., approximately parallel to the strike of the surrounding schists. The veins of commercial significance are confined almost entirely to the quartz diorite, and its boundaries mark, in general, the limits of the ore-bodies. The external form of the intrusive body is thus seen to be of particular economic importance. The extreme northern part of the quartz diorite is thought to be a sheet dipping southward at an angle of 20° to 25°. An east-west section along either of the supposedly mined-out North or Rat veins would show the contact between the schist and the quartz diorite to be a saucer-shaped line. The igneous mass, however, is not a simple pipe-shaped body dipping eastward, approximately parallel to the schistosity, and plunging southward. A more complex form is indicated by the schist encountered in the east end of the 200-ft. level on the Blue vein. Detailed study on the orientation of the crystals in the quartz diorite at this place seems to indicate a roll in the flow lines in the intrusive mass. The inference is that here there is either a large schist inclusion or an irregularity in the schist floor rather than an offset in the floor by faulting.

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[2] G. I. Adams: Geology of Alabama. Alabama Geol. Survey *Special Rept.* 14 (1926) 36–38.

[3] G. I. Adams: Reference of footnote 1, 18.

The west contact of the intrusive near the main shaft dips eastward at 30° to 35° but appears to steepen southward. Thin alternating bands of the quartz diorite and schist, weak contact-metamorphic effects, and poor exposures prevent accurate direct dip measurements. Old stope maps indicate a steep eastward dip for the east contact. This has not been verified in the field, as the stopes are now inaccessible. In most places the contact is tight and devoid of any evidence that indicates movement. Much more underground development is necessary before the shape of the intrusive body can be defined.

It is evident from the relatively poor schistosity and linear elements in the quartz diorite that the quartz diorite was intruded into the schist after the schistose structure was mostly formed. The quartz diorite cuts sharply across the schist planes in several places underground, although, in general, the contact parallels the schistosity. The presence of garnet and the development of strain shadows (wavy extinction) in the quartz suggests that the quartz diorite has undergone some regional deformation. In addition, the intrusive rock is sheared in places, especially in the part of the mass south of South Hill. It is thought that the quartz diorite was intruded along planes of weakness in the schist before the last crustal disturbance that formed the old folded Appalachian Mountains had entirely ceased. The quartz diorite, after solidifying, was subjected to a relatively minor amount of deformation and, being more competent than the schist, yielded by clean fracturing under conditions where the schist yielded by flowing. This last feature is considered to be of great importance in explaining the form of the veins and is more fully discussed under the structure of the veins.

Contact Metamorphism.—The metamorphic effects at the contact of the schist and quartz diorite are slight. Muscovite is more abundant than elsewhere and is especially common in the quartz diorite itself. Locally the quartz diorite grades into almost solid muscovite. The schist is generally silicified and cut by barren stringers of white quartz. Pseudomorphs of quartz-sericite aggregates after andalusite (?) are common in some areas.

The paucity of mineralization at and near the contact is interpreted as evidence that the mineralization did not come directly from the quartz diorite mass but was introduced at a later time, although possibly from the same original magma chamber as the intrusive rock.

Economic Geology

The history of mining at Hog Mountain has been briefly discussed in several reports.[4] The mine was worked at irregular intervals from the

[4] W. B. Phillips: Reference of footnote 1, 49–55.
T. H. Aldrich, Jr.: Reference of footnote 1.
G. I. Adams: Reference of footnote 1, 47–50.

date of its discovery in 1839 until obtained in 1890 by Col. T. H. Aldrich. The work before 1890 was done almost entirely on the south end of the intrusive body near South Hill. These workings are caved and so overgrown that it is impossible to get accurate information as to the size and extent of the veins. About 1893, work was begun on the veins in the northern part of the intrusive mass. The company that operated at this time controlled the entire property with the exception of 10 acres of land on South Hill, which remained idle. Many open cuts and partly caved, shallow tunnels furnish evidence of the amount of work done after 1893. The mine was operated continuously until 1915, when it was forced to close by the depletion of the more amenable oxidized ores, the increasing quantity of sulfides in the ore being difficult to treat satisfactorily. It is probable that increased costs, brought about by the world war, were also an important factor in causing the shutdown. The mine was idle from 1916 to August, 1933, when the Hog Mountain Mining and Milling Co. commenced operations.

Production

According to Adams[5] the production of the Hillabee Mining Co. from the years 1893 to 1916 was approximately $250,000. No data on the production prior to 1890 have been obtained. The production returns from the present operations are not yet available, although shipments of concentrates are being made at regular intervals.

Placer Deposits

No placer deposits have been found near Hog Mountain. The gold in the veins is extremely fine, and even in deeply weathered outcrops where the gold is free from sulfide it is exceedingly difficult to obtain recognizable colors in a pan.

Vein Deposits

Aldrich[6] and Adams[7] consider the quartz veins to have formed in shrinkage cracks in the quartz diorite. The field data as now interpreted are opposed to such an origin. The veins are too persistent, both along the strike and to the depth attained, to be of the gash-vein type usually formed by filling of shrinkage cracks. The curvature of the veins, as shown on Fig. 1, is not adequately explained if this origin is correct. Most of the veins strike between N.60E. and east-west and have uniform dips of 45° to 85° to the north. Their distribution has no obvious relation to the periphery of the intrusive body, as would be expected of shrinkage cracks.

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[5] G. I. Adams: Reference of footnote 1, 50.
[6] T. H. Aldrich, Jr.: Reference of footnote 1, 578.
[7] G. I. Adams: Reference of footnote 1, 40.

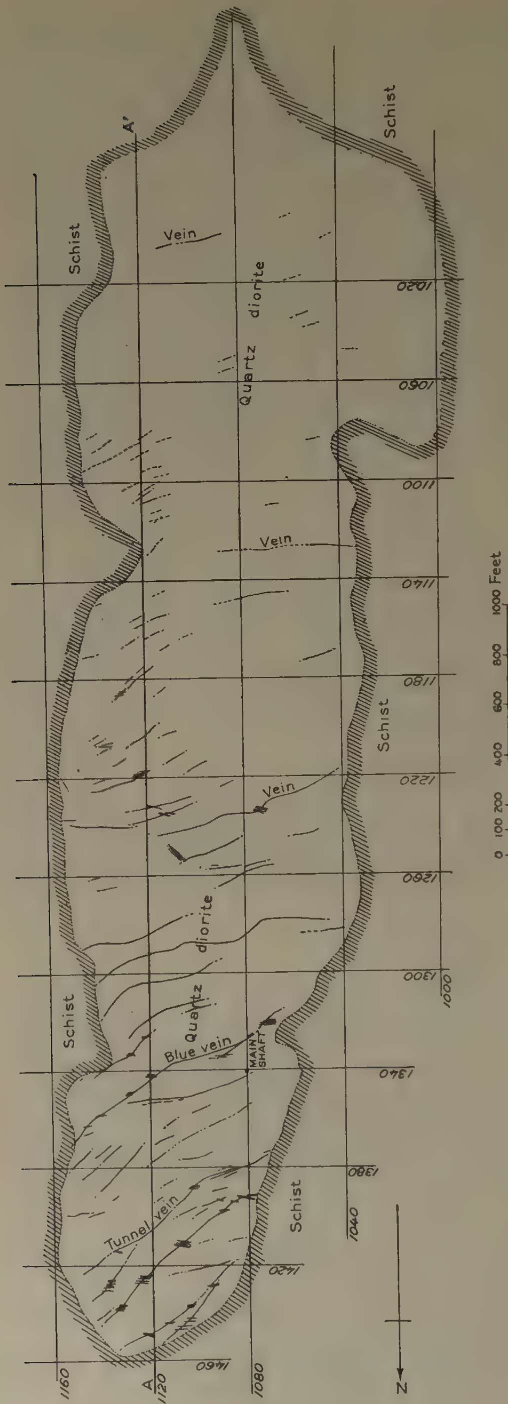

FIG. 1.—GEOLOGIC MAP AND NORTH-SOUTH STRUCTURE SECTION THROUGH THE QUARTZ-DIORITE INTRUSIVE MASS.

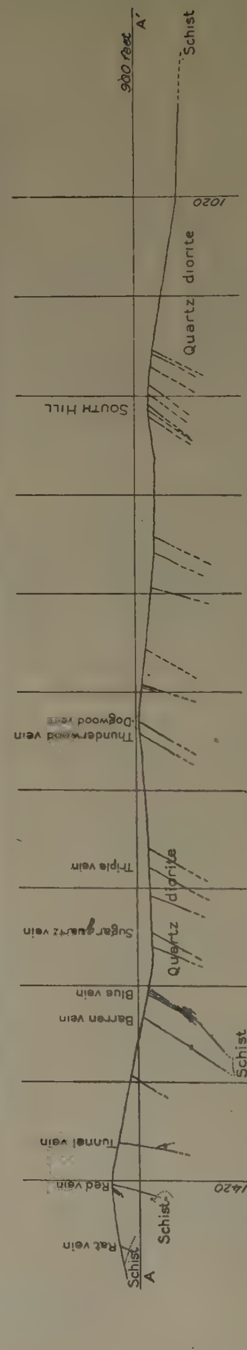

FIG. 2.—CROSS-SECTION *A-A'* ALONG COORDINATE 1120.

The form and distribution of the veins is most readily explained by considering them to be tear faults or flaws related to a northeastward striking thrust fault. Near the end of the period of thrust faulting and after intrusion of the quartz diorite, torsional stresses occurred, which resulted in a relatively small northeast-southwest movement. The schist yielded along planes of schistosity, and flaws or tears were developed in the more competent quartz diorite.

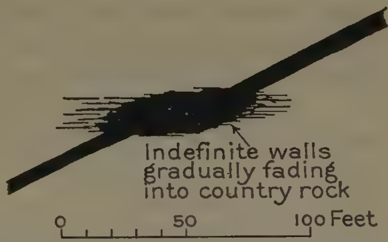

FIG. 3.—PLAN OF SHEAR ZONE CROSSING VEIN.

The veins of economic importance are confined almost entirely to the quartz diorite. Where followed towards the schist-quartz diorite contact, they commonly split into many stringers which gradually pinch out near the contact. In a few places the veins widen near the contact and form pipe-shaped orebodies. An example of this condition is seen on the west end of the Blue vein on the 200-ft. level where the vein widens near the contact and forms a replacement body of quartz and mineralized quartz diorite that was mined for a width of about 20 ft. At the east contact on the 200-ft. level of the Blue vein, the quartz stringers are so numerous that an attempt has been made to mine them. In several places small veins of quartz are found along the contact.

Shear zones that strike nearly due east and dip uniformly to the north are conspicuously developed in the quartz diorite and are present, but less noticeable, in the more poorly exposed schist. Many of the shear planes cross the veins; others bend and merge with the veins. They appear to be essentially contemporaneous with the vein fissures but in some localities are later than, and offset, the vein fissures. This relation is much obscured by late mineralization but is indicated, however, in the "shear zone stope" on the 100-ft. level of the Blue vein (Fig. 3). The shear planes are not as a rule persistent, although in some places the zones have been followed as much as 200 ft. with but little variation in character. Most of the larger stopes and pits show prominent shear zones that cross the veins at angles usually less than 45°.

The mineralizing solutions were introduced after practically all the regional deformation had stopped. The solutions not only deposited their mineral constituents in such openings as existed, but in many places the quartz diorite was replaced, as is shown by the preservation of the granitoid texture in rock that is in large part composed of introduced quartz. Some of the orebodies, especially near the shear zone crossings, have irregular fading contacts, and the completely silicified quartz diorite changes gradually to almost unaltered intrusive rock (Fig. 3). In detail many of the small veinlets and stringers have irregular inter-

locking contacts with the adjacent quartz diorite. Many of the veins, however, have well formed walls, coated with thin seams of chlorite and sericite. Some fissure filling undoubtedly has taken place; but no ribbon structure, comb texture, or other indication of inward growth from the walls has been seen. It is thought on the basis of the evidence now available that replacement was probably more important than fissure filling in the formation of the veins.

Pre-existing tear fissures, shear zones and joint planes in many places have apparently influenced ore localization. In places one wall of a vein may persist and the other wall be deflected along pre-mineral fracture planes. At other places both walls may be deflected along breaks, and the attitude of the vein changed appreciably. Joints dipping less than 20° are prominent in the Blue vein stopes. Large blocks of country rock are present in several of the veins. These blocks are bounded by smooth walls coated with chlorite or sericite.

Both Becker[8] and McCaskey[9] recognized two stages of quartz in the deposits of the Southern Appalachians, in which one stage carries the valuable minerals, and the other quartz is barren. At Hog Mountain all gradations between the two types of quartz are found. The available evidence suggests that there was a continuous deposition of quartz with a gradual change of the valuable mineral content, rather than two separate periods of deposition.

A few small fissures and seams have been formed since the principal veins were deposited. These late seams were partly filled with flat rhombohedrons and "dog-tooth" crystals of calcite and a little clear quartz. There has also been, in a few places, slight fracturing of the ore-bearing veins. This movement is commonly parallel to the pre-mineral shear zones, but a few of the fractures dip to the south. Vugs are common, and marcasite, probably of supergene origin, occurs with the calcite below the water level. The seams where cut underground commonly act as water courses.

Many small veins and lenses of mineral-bearing quartz are present in the schist. These veins and lenses are too small to be of commercial significance. The schist probably did not furnish paths of easy circulation such as were available in the quartz diorite, and in addition was apparently more difficult to replace.

If the origin of the veins, assumed to be mineralized tear faults, is correct, en echelon lenses of ore should be expected.

Oreshoots.—The best ore commonly is localized in shoots in the wider parts of the veins; where the width increases, the unit value of the ore is generally greater. Maximum widths are found either where the veins

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[8] G. F. Becker: Reconnaissance of the Gold Fields of the Southern Appalachians. U.S. Geol. Survey 16th *Ann. Rept.* (1895) pt. 3, 285.

[9] H. D. McCaskey: Reference of footnote 1, 39.

are crossed by shear zones or where there are sharp changes in the strike or dip of the veins.

According to T. H. Aldrich, Jr.,[10] and judging from old stope maps, there was a tendency for the oreshoots in the oxidized zone to plunge about 45° to the east. This does not seem to hold in the present workings, as the long axis of the "shear zone" stope and 200-ft. level stope on the Blue vein dips nearly 60° to the west (Fig. 4). Sufficient work in depth has not been done to justify any generalizations about the direction of plunge of the oreshoots.

The Barren vein was so named because of its large outcrop of barren quartz. Good ore was found, however, about 15 ft. below the surface. It is to be expected in this type of ore deposit that not all of the oreshoots will outcrop at the surface.

No systematic sampling has been done on the veins but the present operators report that their mill heads run about 0.2 oz. per ton in gold.

Mineralogy

The minerals in the ore deposits are typical of the deep vein or hypothermal zone. They are few in number and simple in composition.

Quartz.—By far the most abundant mineral in the veins is quartz. Below the water level the quartz is generally massive, very vitreous, dark gray or bluish gray where associated with gold, and usually light gray or white where free of values. The peculiar dark color and greasy appearance is possibly caused by myriads of inclusions and vacuoles. These are so numerous that a process was developed for making the ore porous by heating, which caused the included materials to expand, thus shattering the rock.[11] Most of the swarms of inclusions have not yet been identified, as they are difficultly seen even under a high-power microscope. Possibly because of internal stresses caused by the vacuoles and inclusions, the quartz in the stopes frequently snaps and cracks, and it is difficult to keep loose fragments barred down. The fresh dark gray quartz, where unaltered, appears massive in the hand specimen, but under the microscope an irregular granular texture is seen. No vugs have been found.

Near the surface the dark gray quartz changes to a loose sugary aggregate of white quartz that suggests quartzite or even sandstone. Under the microscope the sugary quartz is seen to be relatively free from vacuoles and inclusions. Many cracks extend in all directions, as if the quartz had been shattered. The inference is that the sugary texture has been developed in the quartz by relief of the internal pressure and removal of most of the vacuoles and inclusions. In places on the surface, pieces of

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[10] T. H. Aldrich, Jr.: Personal communication, 1934.

[11] T. H. Aldrich, Jr.: Reference of footnote 1.

sugary quartz that contain grains and irregular particles of dark gray quartz are not uncommon.

In the oxidized zone both types of quartz show a prominent sheeting or parting that is inconspicuously developed in the quartz below the water level. This parting may represent a structure that is inherited from the original quartz diorite and accentuated by weathering.

A third type of quartz occurs sparingly with calcite in partly open fissures. This quartz is clear, glassy and crystalline; the crystals project into small vugs. The quartz exhibits no other distinctive features and apparently is of no economic significance.

Sericite (Muscovite).—Sericite is widespread throughout the entire area. It is found in thin layers in the quartz but is more abundant in the walls than in the veins. In places the individual mica plates are as much as ¼ in. in diameter. Sericite is scattered through the entire quartz-diorite mass and is especially common at a few localities near its border. Sericite occurs with chlorite in narrow seams along the walls of the veins.

Pyrrhotite.—Pyrrhotite is by far the most abundant sulfide in the ore minerals. It occurs usually in small stringers through the quartz but in places forms masses a foot or more across. Pyrrhotite has been seen in small cracks and veinlets that cut arsenopyrite.

Chalcopyrite.—Very small amounts of chalcopyrite are present. Small seams, which cut pyrrhotite, were seen on the 200-ft. level of the Blue Vein. Chalcopyrite is not present in sufficient amounts to pay for the extraction of copper from the sulfide concentrates.

Pyrite.—Pyrite is of rare occurrence and has not been seen in the better ores. Pyrrhotite is commonly called pyrite by the miners. Very little pyrite has been seen in any quartz veins. The mineral is more common in the schist than in the quartz diorite.

Arsenopyrite.—Arsenopyrite occurs in small amounts widely scattered through the veins. The mineral is rarely recognized but was noted on the tunnel level of the Red vein. A few crystals were picked up on the mine dump near the main shaft, and one specimen was obtained from the 200-ft. level of the Barren vein.

Gold.—No free gold has been seen except in the flotation concentrates under the microscope. The mine operators report having seen a few very fine colors in panned surface ore. About 50 per cent of the gold in the sulfides is reported to be taken out by amalgamation. The gold is all very finely divided and is at least in part intimately mixed with or inclosed in the sulfides.

Sphalerite.—Zinc sulfide occurs in small amounts in much of the ore. The mineral is finely divided and is difficult to see. A specimen obtained on the dump at the main shaft is coal-black and is hard to distinguish from the greasy dark gray quartz. An analysis of one flotation concentrate

sample is reported by the company assayer to have run 3.32 per cent zinc, but this assay is probably above the average.

Galena.—Galena is reported to be present locally, and determinations run on the flotation concentrates show small amounts of lead (± 0.05 per cent). No galena has been seen.

Bismuth.—Bismuth minerals are reported to have been found during the operations prior to 1916. None of the material has been obtained and the presence of bismuth has not been checked.

Silver.—Silver is reported by T. H. Aldrich, Jr.,[12] to have been present in appreciable amounts in ores near the surface, but numerous recent determinations have detected hardly more than traces in the sulfide ores. Flotation concentrates are reported to carry about 0.30 oz. of silver a ton.

Other Minerals.—Marcasite, manganese oxides, native sulfur and limonite are found in the oxidized parts of the veins, the last named being commonly abundant. Small quantities of chlorite, garnet, tourmaline and calcite are found in the veins locally, and the first three also occur in the wall rocks adjacent to the veins.

Oxidation and Enrichment Zones

A considerable amount of rock must have been eroded before the present surface at Hog Mountain was developed. Aldrich[13] has estimated that a thickness of approximately a mile was thus removed. No evidence confirming this estimate was obtained during this survey, although in view of the general history of the Appalachian region[14] and the amount of rock removed in other sections, this figure, if in error, appears low. The gold veins exposed at Hog Mountain are of the deep-vein-zone type, and it is probable that they extended upward some distance into the eroded terrane. A large quantity of gold was probably lost by this erosion.

According to Aldrich,[15] before mining operations began the ground-water level at Hog Mountain stood about 50 ft. below the surface. Above the water level is a zone of more or less thorough alteration (saprolite), and below it is about 10 ft. of partly decomposed rock that grades into fresh unaltered sulfides (Fig. 4). The deepest evidence of oxidation seen is a few limonite stains on the 100-ft. level on the Blue and the Barren veins. A little marcasite is also present on the 100-ft. level. No evidence of oxidation or supergene enrichment has been found on the 200-ft. level or in the 200-ft. stope on the Blue vein.

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[12] T. H. Aldrich, Jr.: Personal communication.

[13] T. H. Aldrich, Jr.: Reference of footnote 1.

[14] A. I. Jonas: Structure of the Metamorphic Belt of the Southern Appalachians. *Amer. Jnl. Sci.* (1932) **24**, 228–243.

[15] T. H. Aldrich, Jr.: Reference of footnote 1.

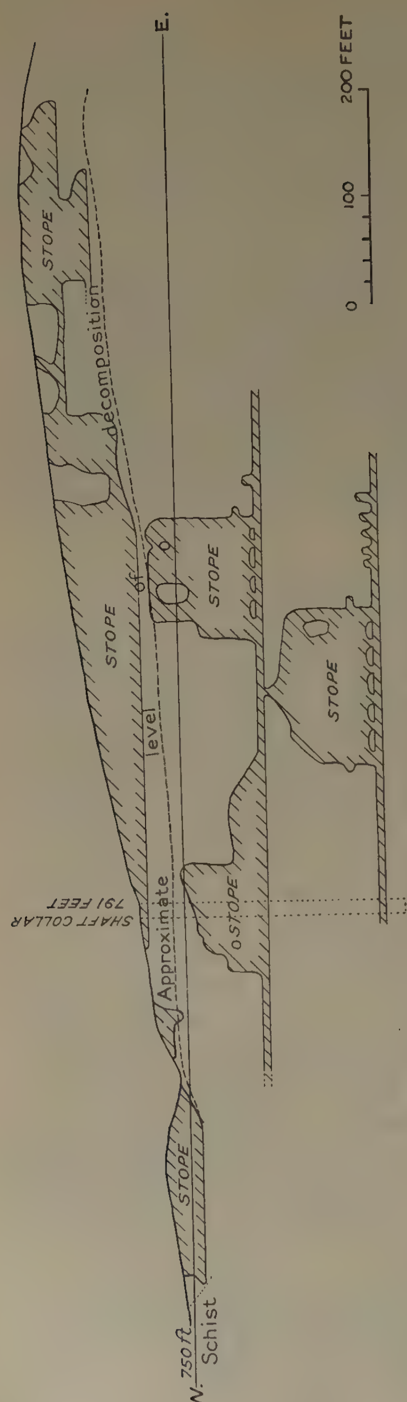

FIG. 4.—LONGITUDINAL PROJECTION OF BLUE VEIN, SHOWING STOPED AREAS.

Secondary enrichment of the gold-bearing lodes is believed by Graton[16] to have occurred in North and South Carolina, although the evidence was not conclusive. It is also likely that enrichment has occurred in many places in both Georgia and Alabama. Adams,[17] quoting T. H Aldrich, Sr., states that at Hog Mountain the ore was richer at the zone of gradation from oxidized ores to sulfide ores, and some concentration of gold near open fissures has been reported by the present operators. There is thus good evidence that some supergene enrichment of the gold has occurred at Hog Mountain. The enrichment must have been very slight, however, as the assays from the deepest workings are reported to be about the same as the assays from the old oxidized workings. It is not possible to say whether the slight enrichment was chemical (small quantities of manganese and chlorine are found in the ore), or a simple mechanical settling of the heavier particles of gold. In either event the secondary enrichment is considered to be of minor importance.

Genesis of the Ores

The veins of economic importance at Hog Mountain are found only in the quartz diorite; they split and pinch out near or in the surrounding schist. The explana-

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[16] L. C. Graton: Reconnaissance of Some Gold and Tin Deposits of the Southern Appalachians. U.S. Geol. Survey *Bull.* 293 (1906) 65–69.

[17] G. I. Adams: Reference of footnote 1.

tion of this localization is found in the peculiar set of conditions at Hog Mountain. Adams[18] states: "The veins were probably formed by rising solutions which were differentiated from the regional magma at abysmal depth." This generalization may be essentially correct, but the veins were formed in the quartz diorite after the intrusive rock was solidified at least sufficiently to enable regional deformation to be expressed in it by fracturing in preference to rock flowage. The conclusion is that, although the quartz diorite and the mineralizing solutions may have originated in the same magma chamber in depth, an appreciable amount of time must have lapsed after the quartz diorite was intruded and before the ore-forming solutions ascended. The quartz diorite acted in the role of the invaded country rock, and the mineral-bearing solutions, although possibly from the same ultimate source as the quartz diorite, cannot be associated too closely with the intrusive mass. The reason the quartz diorite was mineralized in preference to the schists is most readily explained by the different physical properties and, to a lesser extent, by the chemical properties of the two rocks.

Factors Affecting Development

Transportation.—Hog Mountain is about 13 miles from Alexander City, a station on the Central of Georgia Railroad. The gravel and dirt road between the mine and the railroad is partly improved and is passable in most weather. Concentrates are shipped in sheet-iron cans, which are trucked to Alexander City and shipped by rail to the Nichols Copper Co. smelter in New York. The charges for this long freight haul constitute an important item in the total cost of extraction.

Labor.—Unskilled labor, both white and colored, is plentiful and is paid $1.50 per day and up. Board and lodging are furnished at the mine for 75¢ per day. It is difficult, however, to obtain an adequate number of skilled miners. Most of the workmen are drawn from the near-by farming communities, but a few are obtained from the coal and iron mines near Birmingham. Almost none of these men has had experience in hard-rock mining. The labor turnover has been considerable, and it is to be expected that where the labor is drawn from farms the seasonal turnover will be greater than is common in most mines.

Timber.—Timber is abundant throughout the region, but is chiefly second growth short-leaf pine and several varieties of oak. A few long-leaf (turpentine) pines are available, but most of these trees have been cut. The timber at present used in the mine is mostly the short-leaf pine and smaller amounts of white oak. The ground in the mine stands well and requires a minimum of timber.

Water.—Water for mine and mill use is not available at Hog Mountain but is pumped from Allen's Branch, a stream about one mile to the north-

[18] G. I. Adams: Reference of footnote 1, 40.

east. Water for drinking purposes is obtained from a small spring near the mess hall. The mine yields a small amount of water that is easily handled.

Power.—All power is furnished by the Alabama Power Co. over a 12-mile line from Alexander City to the mine substation.

Milling.—No attempt has been made to study thoroughly methods of milling the Hog Mountain ores, but a few remarks may be of value. After considerable experimenting, the present operators installed flotation in preference to amalgamation, cyanidation or other process. The

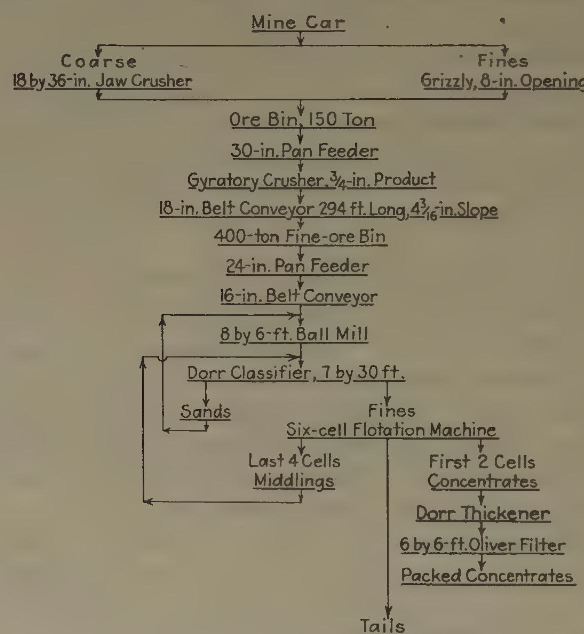

FIG. 5.—FLOW SHEET OF HOG MOUNTAIN MILL.

flow sheet of the small mill is given in Fig. 5. The mill is still in an experimental stage of development, and changes are constantly being made.

A peculiarity of the Hog Mountain ore is the exceptional rapidity with which the sulfides oxidize. Concentrates from the flotation machines, when dried on a filter press and stacked, become warm in about a day. The concentrates must be stored on noncombustible material such as concrete and are shipped in sheet-iron cans in order to avoid danger of fire. After a few days' storage, the dried concentrates become burned to a hard red clinker. The rapid oxidation has caused some difficulties in the milling, and the best results are obtained by taking ore directly to the mill from the mine with a minimum of intermediate storage. Some oxidation in the stopes cannot be avoided where shrinkage stoping

is used. The rapid oxidation may partly account for the variable results reported from cyanidation experiments and the obviously incorrect statement that the sulfides are largely pyrite and marcasite.[19]

The recovery of gold in the mill is reported to be about 90 per cent, and the concentrates usually carry about 3.0 oz. of gold per ton.

Hog Mountain Mine

The veins now being worked at Hog Mountain are opened by a vertical shaft 215 feet deep from which two levels have been driven. The 100-foot level is about 1500 feet long and develops both the Blue and

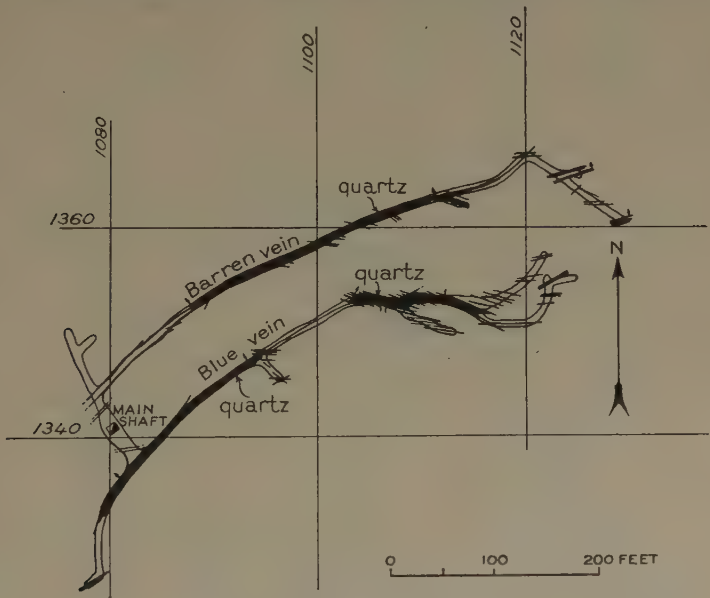

FIG. 6.—PLAN OF 100-FT. LEVEL.

Barren veins (Fig. 6). The 200-ft. level comprises about 600 ft. of workings, also on the Blue and Barren veins (Fig. 7). More work has been done on the Blue vein than on any other vein in the property. Fig. 4 shows a longitudinal section along the vein. The Blue vein varies in width from 1 or 2 ft. up to a maximum of about 20 ft. on the 200-ft. level and in the "shear zone" stope on the 100-ft. level. The average width of the stopes on the Blue vein is 6 to 8 ft. Near the surface, the old pits indicate a split in the vein, but this has not been verified in depth. The Blue vein dips between 50° and 75° to the northwest, with an average dip of about 60°. The Barren vein is somewhat smaller and is stoped about 4 ft. wide. The Barren vein dips somewhat steeper than

[19] E. S. Leaver and J. A. Woolf: Recovery of Refractory Gold in Milling Ores. U.S. Bur. Mines *Rept. of Investigations* 3226 (1934) 5.

the Blue vein and averages probably 70° to the north. No work has been done below the 200-ft. level. All the stoping done by the company operating at present has been on these two levels from the main shaft. Shrinkage stoping has been used entirely and is, in general, satisfactory, although where the veins are deflected along flat joints, some difficulties are met.

The Red and Tunnel veins are opened by an adit and drifts on the veins which total about 1200 ft. of workings (Fig. 8). The stoping and most of the work on these veins was done before 1916. Much of the mining south of the main shaft was carried on through the south drift, which is a shallow tunnel now caved and inaccessible. No maps of this

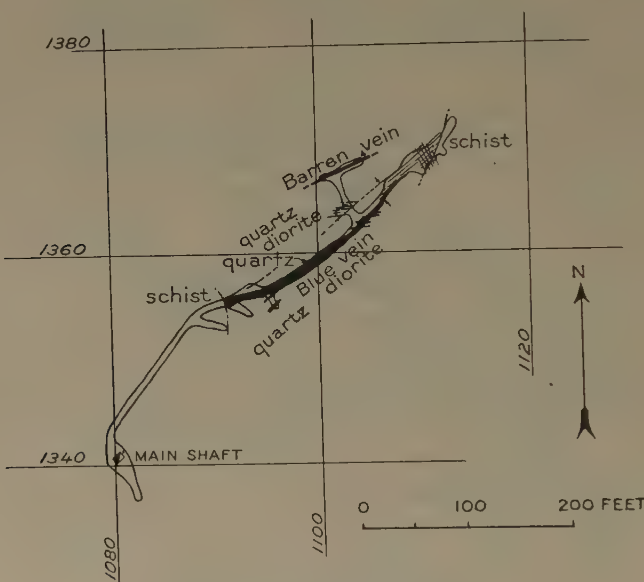

Fig. 7.—Plan of 200-ft. level.

old working level are available. More than three miles of surface cuts have been visited and mapped. Many shallow tunnels, some with lengths of several hundred feet, have been visited and mapped in places, but most of the old tunnels are now caved and inaccessible. The work until 1916 was confined almost entirely to oxidized ores, and it was only in a few places that the sulfide zone was pierced.

At least 16 well defined veins are partly developed by surface cuts and shallow workings. These veins are, from north to south: North, Rat, Red, Tunnel, Pasley, Barren, Blue, Sugar Quartz, Big Pine, Tripple, Little Pine, Champion, Thunderwood, Dogwood, Boundary, and Old Tunnel. In addition to these, others, such as the Jumbo, Rawhide, Smith, and many unnamed veins farther south, have been partly devel-

oped. Most of these veins persist for greater distances along the strike than shown on the map but, owing to the deep weathering, it is impossible to trace veins on the surface without considerable trenching. The

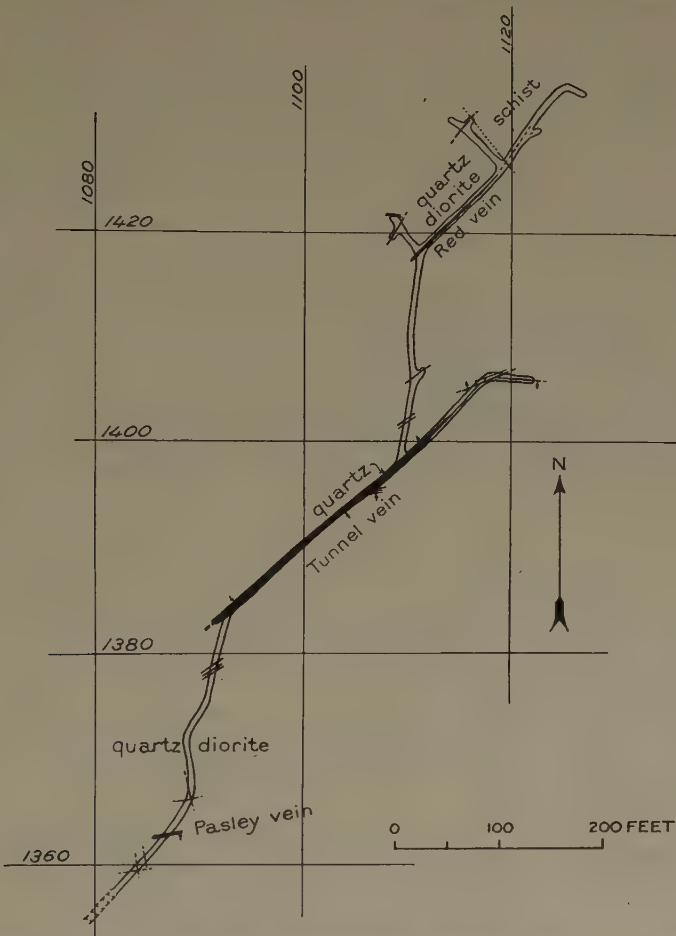

Fig. 8.—Plan of tunnel level.

widths of the veins vary greatly. The 20-ft. width seen on the Blue vein is the maximum, but, judging from abandoned stopes and accessible exposures, veins 3 to 8 ft. wide are common.

DISCUSSION

(*John Wellington Finch presiding*)

H. F. Lunt,* Denver, Colo. (written discussion).—It may be worth while to correct the author's statement that the presence of bismuth in the Hog Mountain ores

* Mining Engineer.

has not been checked. During some months of 1913, H. W. Fox and I operated the Hog Mountain mine. The presence of bismuth was discovered by Mr. Fox early in his experiments on the treatment of the ores. There was not enough to detect in the crude ore, but it was always present in the concentrates. We even reduced some buttons weighing an ounce or more of metallic bismuth. We did not, however, determine its association. We treated some semi-oxidized ore, which had been left broken in a stope on the Barren vein by previous operators and which had become cemented so that we had to blast it out. The records of this operation are not at present available, but my recollection is that there was over 100 tons of this ore, which we concentrated on blankets, making something less than a ton of concentrate carrying about 14 oz. per ton gold, 2 or 3 oz. per ton silver and 12 or 13 per cent bismuth. We tried to find a refiner who would pay for the bismuth as well as the gold and silver, but the best we could do was to get the concentrate treated free, receiving full value for the gold and silver content.

T. H. Aldrich, Jr.,* Birmingham, Ala. (written discussion).—The North vein and Rat vein "bottomed" abruptly at full width against the surrounding schist. There was apparently no dissolving of the schist at the contact and carefully cleaning off the entire bottom of the stope showed no apparent entrance below for the matter composing the vein. I personally attended to this work and am certain of the facts. Mr. Park supposes the veins to be tear faults. I do not see how this could be true. As the quartz-diorite intrusion cooled, after it passed the plastic state and became brittle it still contained considerable heat. Tears at this time might have given the veins a directional crack probably no thicker than a knife edge but undoubtedly they were opened by shrinkage upon the further cooling of the intrusion. As an illustration, the west end of the Blue vein on the surface runs out horizontally to the schist at a width of approximately 4 ft. and there is cut off clean with no crack extending into the schist and no dissolving of the schist; the ending is abrupt and clean cut. It might be thought that they could still be tears and that the motion could have been vertical and the cracks might enter the schist on the bottom side of the intrusion. This in turn could not be true because of the manner in which the North vein and the Rat vein bottom. Mr. Park also suggests that the schist could have yielded along the planes of schistosity, which in turn could not always be true because sometimes the planes of schistosity are perpendicular to the ends of the veins and not parallel with the tear lines.

Upon a visit to Washington some years ago, I had an interview with Mr. McCasky, at which time he showed me under the microscope thin sections of Hog Mountain quartz. These showed plainly a series of sausagelike inclusions separated from one another by about twice their length and approximately three times as long as they were in diameter. There was just a suggestion of a faint connection between them end on end, giving the appearance of a pressure-closed tube. The tubes seemed all to be parallel. These inclusions were about half full of a liquid which Mr. McCasky stated was liquid carbon dioxide. I afterwards devised a process of making this extremely dense ore more porous by heating it to a point where these inclusions would explode and disrupt their walls. The temperature used was about 400° F.

Mr. Park also states that no free gold can be seen except in the flotation concentrates and that a few very fine colors can be seen by panning the surface ore. As a matter of fact, the flotation concentrate shows its gold with great difficulty because of the presence of the oil. Anywhere else in the mill circuit, especially above the floaters ahead of any oil, the gold can be panned with great ease and in great quantity, and on the surface ore, we always judged its value by panning a measured quantity and confirmed it with the assay. The gold is fine and intimately mixed. I have

* Mining Engineer.

never seen any gold in the ore before grinding. It shows a great tendency to attach itself to the sulfides and in some cases the gold grains would be inside of what looked to be drops of ruby silver in which the gold resembled the image blown in a glass marble. Careful panning will show free gold in the sulfide ores just as well as in the surface ores. To illustrate this, the writer made a microscope slide from one assay ton of sulfide ore, panning very carefully in a high-gravity solution of zinc chloride. After concentration on the slide and examination the slide was assayed, a check sample of the ore was also assayed and it was found that 90 per cent of the total gold content was coarse enough to be thus caught and put on the slide. The ore never would amalgamate well even after very fine grinding and preliminary preparation, the difficulty being attached sulfides and an abnormal tendency of the sulfides to dissolve in water fouling the mercury surface. This tendency was many times greater than one would anticipate.

Blanketing was much more practical but gave a concentrate instead of the metal. The recovery by blanketing was well over 50 per cent with very short blankets. A peculiarity of the gold itself is that apparently it contains a metal insoluble in cyanide and instantly soluble in nitric acid. Cyaniding the gold grains turns them red, which color is a residue left on the gold surface not attacked by cyanide. When immersed in a solution of nitric acid these grains immediately become gold color again. As to the silver in the ore, there was a little in the gold itself in the surface ore but a large quantity relative to the gold in the sulfide ores. This was carried by a dark mineral. We never added any silver to the assay charge in assaying cyanide tails of sulfide ore. There was always more than sufficient silver present to make the beads part. This was also true of the head values, but we could not depend upon it because once in a while a rich head would not carry enough silver.

The water level was sometimes deeper than 50 ft. We had one stope on the Blue vein 110 ft. high all in soft ore. The general depth was about 50 feet.

I do not think the surface dissolving of the gold grains was at all due to mineral solvents; I believe that the dissolving action was entirely due to organic acids generated by the decay of vegetation.

Examined under the microscope, the gold grains near the outcrop were rough and pitted like any etched surface. Going further in on the same vein to where the cover would be, say, 50 ft. but still in the zone of decomposition, the grains became smooth and carried many mirrorlike surfaces. The ash of wood from trees on the mountain assayed 60¢. It is extremely doubtful whether the present flotation process takes best advantage of the manner of occurrence of the gold in the ore either technically or economically, and because of the long distance of shipment and smelter charges cyanide would be far preferable; 92 per cent of quartz gangue that does not need it is ground fine in order to effect the fine grinding of the 8 per cent of sulfides that does need it.

A historical fact that has never been mentioned in any paper is that on the peaks of both Big Hog and Little Hog and both facing the west are piles of rock apparently remaining from the "Smoke Talk" days of the Indians.

C. F. Park, Jr. (written discussion).—The arguments advanced in support of the contention that the veins occupy fractures formed by shrinkage of the cooling magma do not seem to hold for the reasons already advanced. Shearing in a northeastward direction would tend to form tension cracks striking northwestward. Such tension cracks would, in a relatively homogeneous mass, form in regular systems such as that at Hog Mountain. It is thought that shrinkage cracks would show some arrangement dependent upon the border of the intrusive body; shrinkage cracks are also generally of the gash-vein type.

Veins similar to those at Hog Mountain and related to zones of shearing are found in several places in the Southern Appalachians. One example in particular is

the Dutch Bend mine, about five miles southeast of Hog Mountain. At this place the veins are mostly confined to a quartz-diorite dike between 100 and 200 ft. wide. A few veins can be followed into the adjacent rock, which is the Wedowee schist, as at Hog Mountain. The veins occur at intervals varying from 100 ft. to more than 100 ft. They strike at angles approximately 30° from the strike of the dike, and the dips are all southeastward. The veins pinch and swell; lenses are common and are customarily connected by narrower bands of quartz. These veins are thought to occupy tension cracks, and it is not seen how they could be interpreted as filled shrinkage fractures.

It is to be expected that mineralizing solutions would penetrate all available openings, and the suggestion that the veins occupy fractures related to shear zones is not meant to imply that all the quartz bodies found occupy such fractures. These fractures, however, are thought to have played a dominating part in the control of the circulating solutions.

In the discussion it is also stated that the schist could not everywhere yield along planes of schistosity because in some places the planes of schistosity are perpendicular to the ends of veins. It should perhaps be emphasized that the veins as now found were formed after practically all movement in the schist had stopped; the vein fractures are considered to have formed during the movement. The veins are not simple filled fissures but are thought to be, in part, of replacement origin. A contact between a fractured brittle rock and a relatively impervious layer is a favorable place for the localization of replacement orebodies.

W. W. Simmons, who has assayed the Hog Mountain ores during recent months, reports very little silver and states that silver must frequently be added in assaying. The smelter returns from the ore shipments during 1934 also indicate low silver values.

Quicksilver Deposits near Little Missouri River, Southwest Arkansas*

(PRELIMINARY REPORT)

BY J. M. HANSELL† AND J. C. REED†

(New York Meeting, February, 1935)

CINNABAR was discovered in southwestern Arkansas on Little Missouri River in sec. 1, T.7S., R.26W., in April, 1930, and near Antoine Creek in sec. 28, T.6S., R.23W., some 15 miles farther east in May of the same year. It was not, however, until June, 1931, that cinnabar was identified as such in a specimen from the original discovery area sent to W. M. Weigel[1] by Walter F. Hintze of Murfreesboro. Almost simultaneously[2], in July, 1931, Moritz Norden of Hot Springs identified specimens from the Antoine Creek area as cinnabar.

Immediate interest in the district followed the identification of cinnabar and by January, 1932, the district was known to extend as a mineralized belt about one mile wide trending east-northeast from sec. 13, T.7S., R.27W., in Howard County across central Pike County and into Clark County to sec. 19, T.6S., R.23W., thence extending southeast into sections 33 and 34 of the same township. Since then, cinnabar has been found in sec. 6, T.7S., R.22W., thus giving a total east-west length to the district of approximately 30 miles.

Interest focused mainly on the two discovery areas, with the result that mining development has progressed most rapidly in those localities. In the Antoine Creek area the Arkansas Quicksilver Co. has done considerable exploration work and has retorted the high-grade ore so obtained. In the Little Missouri area the Southwestern Quicksilver Co. has had a 12-ton rotary furnace in more or less continuous operation since April, 1932, and has been the largest producer in the district.

In March, 1934, the United States Geological Survey began a study of the Arkansas quicksilver district, which was made possible by an allotment of funds from the Public Works Administration. Until

* Published by permission of the Director, U.S. Geological Survey. Manuscript received at the office of the Institute Nov. 26, 1934.

† U.S. Geological Survey, Washington, D.C.

[1] W. M. Weigel: New Quicksilver Discoveries. *Eng. & Min. Jnl.* (1931) **132**, 495–497.

[2] G. C. Branner: Cinnabar in Southwestern Arkansas. Ark. Geol. Survey *Inf. Circ.* 2 (1932) 5.

June 25, the party was under the direction of John C. Reed, the other members being J. M. Hansell and R. C. Becker, assisted by H. A. Millar, T. E. Jones, J. T. Young and John Wilson, Jr. On June 25, Mr. Reed left the party for another assignment and Mr. Hansell had charge of the work until the survey of the area described in the present paper was completed, about Sept. 1. Thus a large part of the preparation of this report fell to Mr. Hansell. The field work included the preparation

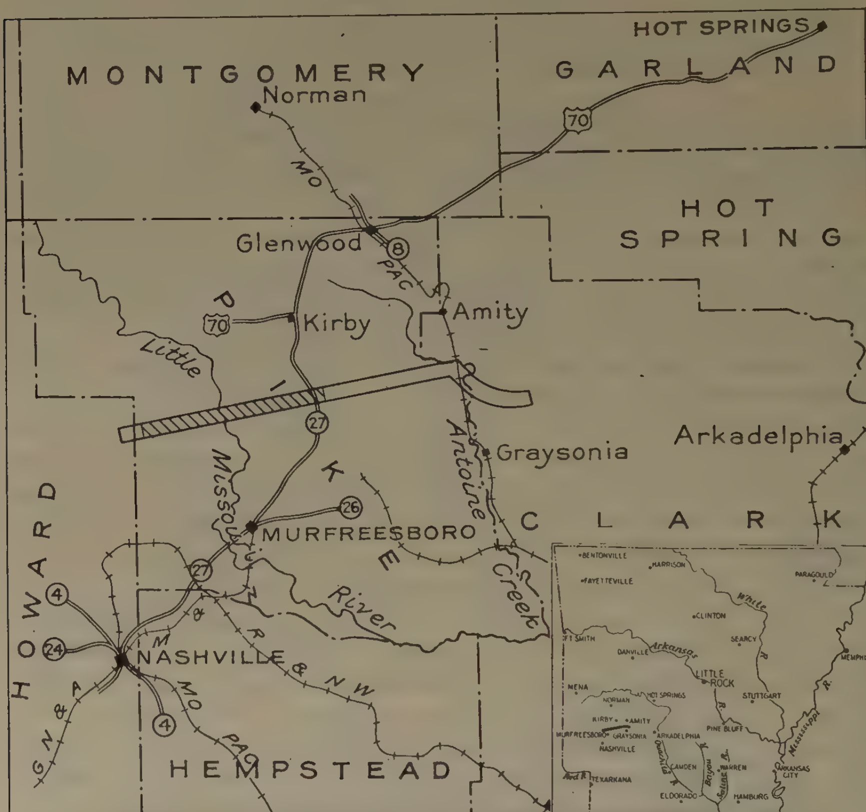

Fig. 1.—Location and extent of Arkansas quicksilver district. Geology of shaded area shown in Fig. 2.

of a topographic map on a scale of 1/24,000 with a 20-ft. contour interval to serve as a base for the adequate representation of the geological and other features of the district. The mapped area extends from ½ mile east of State Highway 27, near the middle of the district, westward for 12 miles to within 2 miles of the west end of the district, or within 1 mile of the Howard County line (Fig. 1). Its average width is 1½ miles. It is with this part of the district that the present paper deals specifically. Early in September the field mapping and studies were extended into

the eastern part of the district near Antoine Creek, and on their completion a report embodying the results of the work in both parts of the district will be prepared and published.

The writers wish to express their appreciation for the information and aid supplied by those interested in the district. Especial acknowledgment is made to Mr. Leo Yount and Dr. N. H. Stearn, of the Southwestern Quicksilver Co., for the mining, furnacing, and extensive geological records that were made available to the party, and for their courtesy and hospitality throughout the entire period of work in their part of the district.

Geography

The locations of the Arkansas quicksilver district and the part described in this paper are shown in Fig. 1. The eastern part of the mapped area is accessible by State Highway 27, the main highway between Hot Springs some 50 miles to the northeast of the area and Murfreesboro 9 miles to the south. The western end of the district is accessible by county roads from both Murfreesboro and Nashville. A road, in part improved by the Civilian Conservation Corps, runs through the area from east to west, connecting Highway 27 with the county roads to the west. This east-west road is passable except in times of high water, when the fords across the streams, especially the Little Missouri, cannot be used.

The quicksilver district is near the southern edge of the Athens Plateau, a belt of country about 15 miles wide between the Ouachita Mountains on the north and the Gulf Coastal Plain on the south. The plateau is dissected by south and southeast-flowing major streams, which, with their east-west tributaries, form a lattice type of drainage pattern. The southward-flowing Little Missouri is the major stream of the mapped area and crosses it about midway between its ends. Cowhide Creek, one of its tributaries, heads near Highway 27 and flows west in a broad valley.

The interstream areas form more or less even-crested ridges trending east-northeastward, which in the Little Missouri area have a general altitude of about 750 ft. above sea level although a maximum altitude of 900 ft. is reached. The maximum relief of the area, 350 ft., is along the Little Missouri, and the minimum, 100 ft., is along Highway 27 on the drainage divide between Antoine Creek on the east and the Little Missouri on the west.

Geology

Three Carboniferous formations, Stanley shale, Jackfork sandstone and Atoka formation, each approximately 6000 ft. thick, have been

recognized on the Athens Plateau[3]. All of these formations are now regarded as of Pennsylvanian age[4]. These rocks have been greatly folded and faulted and as a result they dip at high angles and are exposed in several belts with an east-northeast trend. The folding and faulting of the rocks of the Athens Plateau and of the Ouachita Mountain anticlinorium just to the north were produced by mountain-making forces in the form of thrusting from the south in middle Pennsylvanian time[5].

The sandstones and shales of the Athens Plateau pass southward beneath the gently southward-dipping Lower Cretaceous sediments of the Gulf Coastal Plain. Within the area covered by this report the Cretaceous rocks are represented by the Pike gravel member of the Trinity formation.

The Rocks and Their Distribution

Stanley Shale.—In the Little Missouri River part of the Arkansas quicksilver district the Stanley shale has an exposed thickness of about 2500 ft. (Fig. 2), or less than half its normal thickness on the Athens Plateau[6]. It is dominantly a grayish black clay shale containing many beds, ½ to 6 in. thick, of fine-grained sandstone and a few beds of fine to medium-grained quartzitic sandstone. Where weathered the shale has a characteristic greenish brown color and the sandstone has become yellowish or gray-white and soft. About 1300 ft. below the top of the Stanley there is 300 to 325 ft. of alternating sandstone and shale with an estimated ratio of three parts sandstone to one part shale. This relatively more sandy horizon is indicated on Fig. 2; it forms a pronounced ridge traceable from one end of the area to the other, and is the most important carrier of cinnabar. Overlying this member, and separated from it by 150 to 200 ft. of shale, is another sandstone horizon about 100 ft. thick, which in most places is soft and poorly exposed but which may be recognized nevertheless at many places within the mapped area. Another sandstone member about 150 ft. thick is present in the Stanley shale about 2000 ft. below its top in the east end of the mapped area, but appears to be cut off by a thrust fault about midway between Highway 27 and the river.

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[3] H. D. Miser and A. H. Purdue: Geology of the DeQueen and Caddo Gap Quadrangles. U.S. Geol. Survey *Bull.* 808 (1929).

[4] H. D. Miser: Carboniferous Rocks of Ouachita Mountains. *Bull.* Amer. Assn. Petr. Geol. (1934) **18**, 971–993.

D. White: Age of Jackfork and Stanley Formations of Ouachita Geosyncline, Arkansas and Oklahoma, as Indicated by Plants. *Idem*, 1010–1017.

B. Harlton: Carboniferous Stratigraphy of the Ouachitas with Special Study of the Bendian. *Idem*, 1018–1037.

[5] H. D. Miser: Structure of the Ouachita Mountains of Oklahoma and Arkansas. Okla. Geol. Survey *Bull.* 50 (1929) 26.

[6] H. D. Miser and A. H. Purdue: Reference of footnote 3, 60.

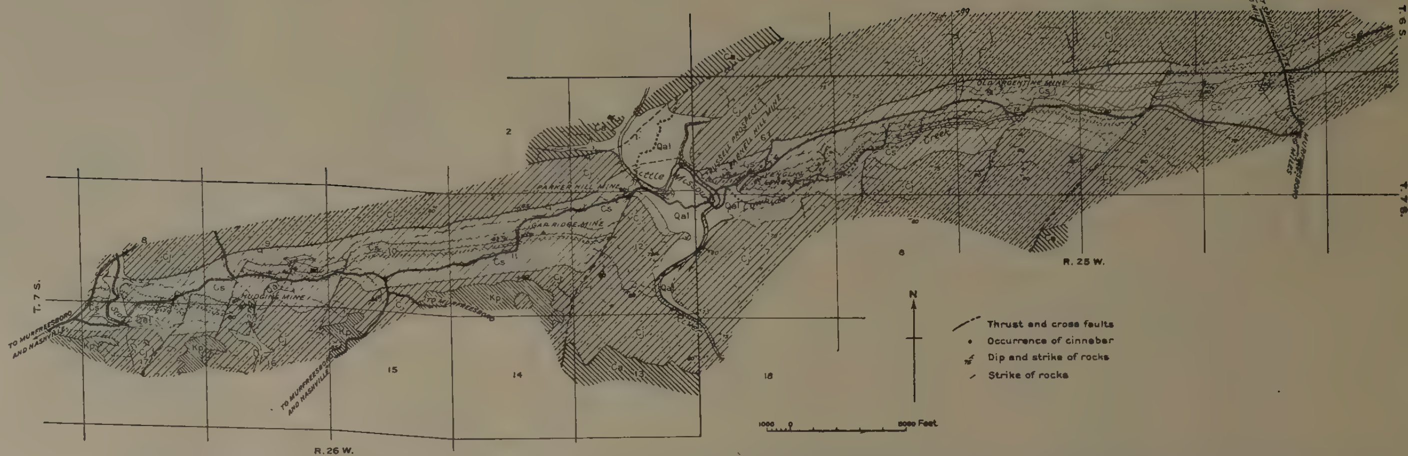

FIG. 2.—GEOLOGIC MAP OF QUICKSILVER DEPOSITS NEAR LITTLE MISSOURI RIVER, PIKE COUNTY, ARKANSAS. *Qal*, alluvium (Quaternary); *Kp*, Pike gravel member of Trinity formation (Lower Cretaceous); *Ca*, Atoka formation (Pennsylvanian); *Cj*, Jackfork sandstone (Pennsylvanian); *Cs*, Stanley shale (Pennsylvanian), sandstone beds indicated by stipple. Geology by J. M. Hansell, J. C. Reed and R. C. Becker.

Except for the well defined ridge formed by the 300-ft. sandy horizon within it, the Stanley shale forms a valley about ½ mile wide trending about N.80°E. through the middle of the mapped area. This broad Stanley shale valley is bounded both on the north and on the south by more or less even crested ridges underlain by Jackfork sandstone.

Jackfork Sandstone.—The Jackfork sandstone is made up dominantly of fine to medium-grained, gray, quartzitic sandstone beds a few inches to 20 ft. thick, with intercalated beds of gray to gray-black clay shale from 1 in. to more than 100 ft. thick. From examination of sections, it is estimated that the formation is made up of 75 to 80 per cent sandstone and 20 to 25 per cent shale. The weathered sandstone is soft and brown. Lenses of fine quartz conglomerate occur mainly in the upper 500 to 600 ft. of the formation. The largest pebble noted was ½ in. in diameter; most of them are about the size of rice grains.

Atoka Formation.—The Atoka formation is composed of about equal parts of sandstone and shale. The sandstone is grayish brown, ordinarily micaceous, and breaks along bedding planes into slabs 1 to 6 in. thick. Much of the shale is black and breaks into smaller fragments than either the Stanley or the Jackfork shale. Both the northern and the southern parts of the mapped area include small areas of the Atoka formation but the map is not extensive enough to include much of it.

Pike Gravel Member of the Trinity Formation.—The Pike gravel member of the Trinity formation (Lower Cretaceous) overlies the Stanley, Jackfork and Atoka formations along the southern border of the cinnabar district and is widely exposed, capping hills and flooring broad plateaulike areas. It is a poorly indurated, clay-bound gravel made up of rounded pebbles, 90 to 95 per cent of which are novaculite and the rest sandstone. Near the base of the member cobbles of sandstone and novaculite 8 to 10 in. in diameter occur, but 1 to 2 in. is the average size of the pebbles.

Alluvium.—Alluvium of Quaternary age floors the valley of the Little Missouri, and is found along Buck and Stony creeks in the western part of the mapped area. Some remnants of higher terrace gravels also remain in these valleys.

Structure

Thrusting.—As mentioned before, Miser has shown how compression from the south in middle Pennsylvanian time caused folding and faulting that resulted in repetition of several more or less parallel bands of the Stanley, Jackfork and Atoka formations across the Athens Plateau[7].

The general trend of the rocks in the limited area covered in this report is about N.80°E. and in most places the dip approaches 80°S.

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[7] H. D. Miser: Reference of footnote 5.

Wherever determinable the tops of the beds are toward the south, not only in the area from the northern contact of the Stanley shale (see Fig. 2) southward across the southern band of Jackfork sandstone into the Atoka formation in what appears to be the normal stratigraphic sequence, but also in the northern band of the Jackfork north of the Stanley shale. Principally on this evidence a thrust fault is believed to separate the northern band of Jackfork sandstone from the Stanley shale lying just south of it.

At no place was the fault plane actually observed but at many places close to the fault the Stanley shale is greatly contorted. At one place in the Stanley, a short distance south of the fault, a small overturned drag fold shows movement up the dip from the south. Its axial plane is about parallel to the dip and may reflect the dip of the major thrust plane. The thrust contact is only slightly wavy and this would also seem to indicate that, at least near the surface, the thrust plane is steep, possibly approaching the prevalent 80° dip of the beds.

The trend of the thrust fault on the surface is nearly but not quite parallel to the strike of the rocks. As no key horizon was recognized for more than a few hundred feet in the Jackfork, the divergence between the outcrop of the fault and the strike of the beds is not readily determinable in the overridden block, but at one place, where the angular divergence is somewhat greater than ordinarily is the case, an individual bed crops out at the fault, whereas the same bed is 150 ft. north of the fault about 600 ft. farther east. The 150-ft. sandstone member in the Stanley about 2000 ft. stratigraphically below its top is cut off by the thrust plane about halfway between Highway 27 and the Little Missouri (see paragraph on Stanley shale, preceding). Thin quartz veining in sandstone is a relatively conspicuous feature along the thrust contact from one end of the district to the other.

The 2500 ft. of Stanley shale exposed in the district represents the upper part of that formation, the remaining 3500 ft. appears to have been cut out by the faulting.

The northern band of Jackfork sandstone apparently is bounded on the north by another thrust, for it adjoins an area of the Atoka formation in which the tops of the beds appear to face the south.

Cross Faulting.—Cross faults with a northeasterly trend offset the Jackfork on the south side of the mapped area and extend into the Stanley to the north, causing similar offsets in the sandstone members within that formation. The offsets along these faults are less in the Stanley than in the Jackfork (Fig. 2) because much of the displacement has been absorbed by the shale between the Jackfork and the sandstone of the Stanley. The two major cross faults, one about a mile west of Highway 27 and the other just west of the Little Missouri, offset the top of the Jackfork along the southern border of the area and extend into the Atoka.

The east side of each block has moved northeast relative to the west side. These cross faults appear to be tears formed during the thrusting and absorbed along the thrust plane without affecting the overridden northern block of Jackfork, with one notable exception about ¾ mile east of the river where the thrust fault itself is offset about 300 feet.

Cross Folding and Fracturing.—In addition to the thrusting and cross faulting, deformational activity has produced an east-west shortening resulting in small sharp folds whose axes plunge about parallel to the dip of the rocks and whose axial planes strike about N.20°–30°E. (See Fig. 2, particularly the strike lines.) The evidence as to the age of this buckling relative to the thrusting and cross faulting appears to be conflicting and the small area covered has not served to establish it definitely.

The cross folds are present in both the Jackfork and the Stanley south of the thrust fault but are not important structural features of the Jackfork in the northern overridden block. The fact that the overriding block is principally affected by this type of folding would seem to indicate that it is in some way connected with the thrust faulting and cross folding. This is in some degree confirmed by the fact that the cross faults are not greatly deformed and by the general accordance of the trends of the axial planes of the cross folds with the trends of the cross faults. The strike lines on Fig. 2 appear to indicate drag folds along the cross faults in the upper part of the Jackfork in the overriding thrust block.

On the other hand, no drag is indicated along the cross faults in the lower parts of the Jackfork or in the Stanley shale and its contained sandstones. In fact, at some places the strikes of these beds near the cross faults are exactly opposite to strikes that would have been produced by drag. Furthermore, some of the cross faults appear to be offset eastward as they pass from the Jackfork on the south into the Stanley on the north.

In the buckling the shales were deformed principally by rock flowage, but the more competent sandstones ultimately fractured and even brecciated, particularly on the noses and limbs of the cross folds as well as along shears and faults. Wherever a fracture system can be made out it is nearly vertical and about parallel to the plunging axis of the cross fold with which it is associated.

Mineralization

Cinnabar is found mainly in the 300-ft. sandstone member of the Stanley shale that lies about 1300 ft. below the top of the formation, but at four places cinnabar has been found in the Jackfork south of the Stanley, and the mineral is reported from one locality at the thrust contact to the north. The distribution of cinnabar occurrences is shown in Fig. 2.

The cinnabar occurs as fracture filling on the noses and limbs of the cross folds, in shear zones, and along cross faults. Not all the fractured areas associated with the buckling, however, are mineralized. A few places have been found where pockets are mineralized in contorted and squeezed shale, and one oreshoot has been uncovered in shale at its contact with sandstone. Dissemination of the cinnabar in the country rock is rarely found, and then ordinarily within an inch of a mineralized fracture.

The mineralized fracture zones are relatively narrow, extending across one or a series of several sandstone beds separated by thin shale members. At no place has mineralization been found more than 10 ft. wide across the strike of the sandstones. It is a peculiar feature that well mineralized beds are side by side with equally well fractured beds that are barren. Possibly the mineralizing solutions did not have access to certain fracture zones. The maximum length along the strike of any mineralized zone opened to date is 140 ft., and at this place mineralization stopped at a horizontal fracture 15 ft. below the surface. General persistence of fracture zones and their mineralization in depth, either vertically or dipping steeply to the east or west, is indicated by the work of the Southwestern Quicksilver Co., whose three mines, Parker Hill, Parnell Hill and Gap Ridge, show no change in the character of the ore at depths of 129, 187 and 225 ft. respectively. The bottom of the Parker Hill mine is about 300 ft. below the surface at the Gap Ridge mine.

Primary minerals associated with the cinnabar include dickite (hydrothermal kaolin) and quartz, and minor amounts of stibnite and pyrite (or marcasite). Stibnite has been found only in Parnell Hill and Gap Ridge mines, and in no great abundance in either. Dickite is the widespread mineral of the district and occurs either with or without cinnabar. At the surface the pyrite has oxidized to limonite and some cinnabar crystals are coated with metacinnabarite, giving them a dark color. At Parker Hill mine native mercury has been found at the surface and also in a pocket at a depth of 113 ft. Where the mercury is found, the cinnabar has wholly or partly disappeared, leaving open limonite-stained fractures, or pockets in the dickite either with or without limonite, in which globules of mercury remain. The formation of the mercury is believed to be due to oxidation of cinnabar after its deposition.

Igneous activity took place in Arkansas in early Upper Cretaceous time[8]. The Magnet Cove igneous rocks, the syenites south of Little Rock, and the diamond-bearing peridotite plugs near Murfreesboro were intruded at this time. The acidic tuffs and conglomerates north of

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[8] H. D. Miser and C. S. Ross: Diamond-bearing Peridotite in Pike County, Arkansas. U.S. Geol. Survey *Bull.* 735 (1923) 311–312.

Nashville are of the same age[9]. The peridotite plugs near Murfreesboro are about 9 miles south of the district along the Little Missouri and the acidic tuffs and conglomerates north of Nashville are about 16 miles distant. Because of the widespread igneous activity in early Upper Cretaceous time and its proximity to the district, it is possible that the hydrothermal solutions that deposited the cinnabar, stibnite, dickite, quartz and pyrite of the district came from some one of these igneous masses. Because of the absence of other evidence of age of the mineralization, it is concluded that probably it took place in early Upper Cretaceous time.

The distribution of cinnabar in a narrow belt 30 miles long suggests that the mineralizing solutions came up along the thrust fault until they encountered the fractured and faulted sandstones of the Stanley. These members lying between thick shales to the north and south offered channels by which the solutions could ascend toward the surface. Where these solutions had access to the cross faults cutting the Jackfork, that formation was mineralized also.

Mines and Prospects

Southwestern Quicksilver Company Mines

The Southwestern Quicksilver Co. has been the only producer of quicksilver in the mapped area and the major producer of the district. Leo Yount began prospecting for cinnabar in August, 1931, soon after the identification of cinnabar from the district. Properties were leased and exploration begun on Parnell Hill in the SW.¼, SW.¼, sec. 6, T.7S., R.25W., on Parker Hill, the original discovery site of the district, in the SE.¼, SW.¼, sec. 1, T.7S., R.26W., and on Gap Ridge in the SW.¼, NE.¼, sec. 11, T.7S., R.26W. During the first three months of 1932, in addition to the intensive prospecting, detailed mapping of the geology of the Little Missouri River part of the district was carried on under the direction of N. H. Stearn, and about 20 square miles of the district were mapped. In April, 1932, a Gould rotary furnace, with a rated capacity of 20 tons per 24 hr. but with an actual treating capacity of 12 tons, was installed on Parnell Hill.

Prospecting consisted in cutting into the sides of the hills toward places where mineralization was known to exist. The steep slopes allowed faces 30 to 40 ft. high to be exposed within horizontal distances of 50 to 75 ft. From these cuts it was possible to work laterally along the strike where desired. The advantage of this type of prospecting over sinking or drifting was in the better opportunity to study the mineraliza-

[9] C. S. Ross, H. D. Miser and L. W. Stephenson: Water-laid Volcanic Rocks of Early Upper Cretaceous Age in Southwestern Arkansas, Southeastern Oklahoma, and Northeastern Texas. U.S. Geol. Survey *Prof. Paper* 154 (1928) 189.

tion. After the preliminary prospecting, it was possible to use the openings that showed the best mineralization as sites for sinking on the ore.

FIG. 3.—GEOLOGY OF PARNELL HILL MINE AND PARTS OF ADJOINING PROPERTIES, SEC. 6, T.7S., R.25W., PIKE COUNTY, ARKANSAS. *Qal*, ALLUVIUM; *Cj*, JACKFORK SANDSTONE; *Cs*, STANLEY SHALE (SANDSTONE BEDS INDICATED BY STIPPLE).

During prospecting the mineralized rock was sorted and the waste discarded in the openings as the work progressed. In the shaft mining, all the rock is hoisted, dumped into bins, and then hand-sorted to a concentrate averaging about 20 lb. of metallic mercury to the ton. The

proportion of waste rock to concentrate of this tenor varies but the average from combined prospecting and shaft mining on Parker Hill and Gap Ridge is estimated to be 6 tons of rock to 1 ton of ore of 20 lb. of mercury per ton[10]. On Parnell Hill it was necessary only to tram the ore to the plant for crushing and furnacing, but during 1934, when all the production came from Parker Hill and Gap Ridge mines, it was necessary to truck the sorted ore to the plant on Parnell Hill, using a company-built ferry across the Little Missouri. Lack of adequate pumps to handle the increased flow of water in both Parker Hill and Gap Ridge mines was one of the factors that caused the company to suspend operations in September, 1934.

Parnell Hill Mine.—The geology of Parnell Hill is shown in Fig. 3. It has also been described by Stearn[11]. The hill is formed by the 300-ft. sandstone member of the Stanley shale and lies a few hundred feet south of the thrust fault bounding the Stanley on the north. The cross-buckling has produced the cross fold at Cut No. 1 and the two small faults east of it at Cut No. 12 and Cut No. 15. The fault in the southeastern part of the area shown in Fig. 3 has offset the sandstone member that forms Parnell Hill about 500 feet south and 1500 feet west. (See Fig. 2.)

Cross fractures are mineralized near the top of the 300-ft. sandstone member at the contact between it and a persistent shale member. At the cross fold mineralization extends across the hill in the shattered sandstone, but economic ore has been found only near the sandstone-shale contact. In cut No. 1, some ore was obtained from the shattered sandstone on the nose of the cross fold and a shaft was sunk to a depth of 14 ft. in the bottom of the cut, giving a total depth from the surface of about 65 ft. In cut No. 12 cinnabar was obtained from an oreshoot pitching at a steep angle to the east at the shale-sandstone contact. This shoot was followed by a shaft to a depth of 87 ft. below the bottom of the cut or 122 ft. from the surface outcrop. The ore contained some stibnite. Mineralization that occurred for a distance of about 140 ft. west from cut No. 12 ended at a horizontal fracture about 15 ft. below the surface. East of cut No. 12 a small rich oreshoot along the small fault was followed to a depth of 187 ft. below the surface.

Parker Hill Mine.—The Parker Hill mine is in a 100-ft. sandstone member within the Stanley shale 400 ft. northwest of the major cross fault on the west side of the river (Fig. 2), and a few hundred feet south of the thrust fault between the Stanley and Jackfork. The geology is shown in Fig. 4. The original discovery of quicksilver in the district

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[10] L. Yount: Personal communication.

[11] N. H. Stearn: The New Quicksilver District in Arkansas. *Min. Jnl.* (Ariz.) (June 15, 1932).

Mining and Furnacing Quicksilver Ore. *Eng. & Min. Jnl.* (1933) **134,** 122–124.

was at the opening in the southwest side of the hill, and much of the native quicksilver has been found there. The best ore has been found in shattered sandstone on the nose of the cross fold and along the small cross fault about 90 ft. east of the fold. This fault strikes N.5–8°E. and dips 60° E. The east side has been offset 8 to 10 ft. north with respect to the west side. A shaft was sunk to a depth of 75 ft. on the nose of the fold and worked for 27 ft. east with good ore to the bottom, but

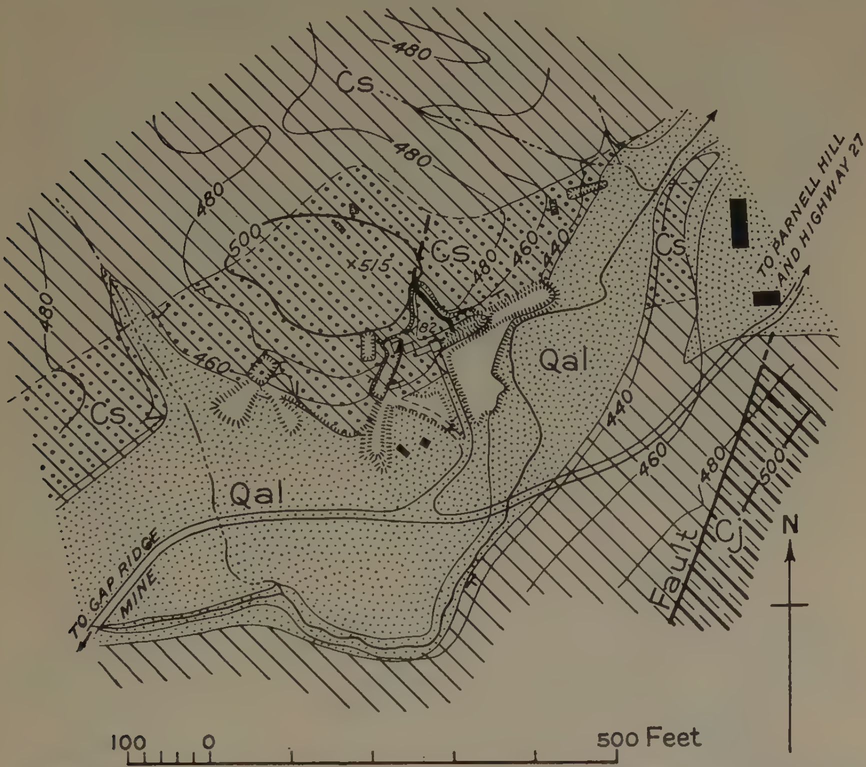

Fig. 4.—Geology of Parker Hill mine, SE.¼, SW.¼, sec. 1, T.7S., R.26W., Pike County, Arkansas. *Qal*, alluvium; *Cj*, Jackfork sandstone; *Cs*, Stanley shale (sandstone beds indicated by stipple).

trouble in retaining the shale hanging wall caused this shaft to be abandoned. A second shaft was sunk 70 ft. west of the cross fault and about 30 ft. east of the nose of the fold, utilizing the east side of the former opening as much as possible. This shaft has a depth of 129 ft. from the surface outcrop. At a depth of 113 ft. a drift was run west 30 ft. to the nose of the fold, and good ore with a width of 6 to 8 ft. was exposed for the entire distance. One pocket containing native mercury was found in this drift. The bottom of the shaft encountered a rapid flow of water estimated at between 300 and 400 gal. per hour. It is believed that this is ground water contained in adjacent sandstone beds and under

head because of the depth of the shaft, 70 ft., below ground-water level, which is approximately river level. Until the flow was encountered very little pumping had been necessary to keep the shaft dry.

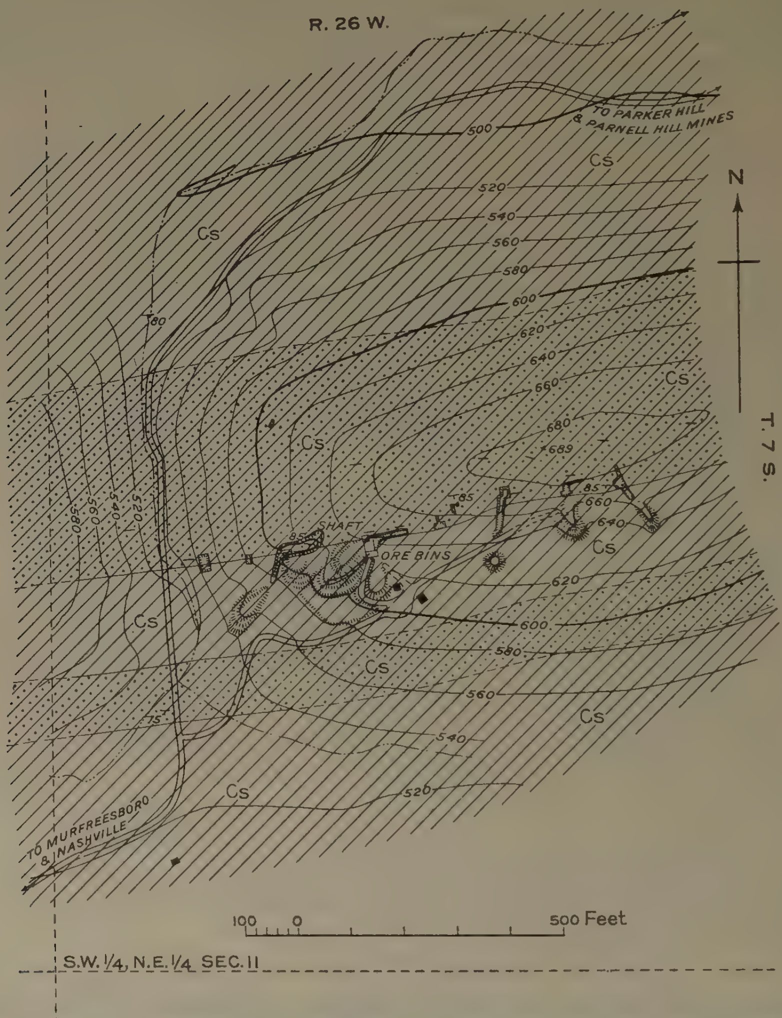

Fig. 5.—Geology of Gap Ridge mine, sec. 11, T.7S., R.26W., Pike County, Arkansas. *Cs*, Stanley shale (sandstone beds indicated by stipple).

Gap Ridge Mine.—The Gap Ridge mine (Fig. 5) is in the same persistent 300-ft. sandstone member of the Stanley shale as the Parnell Hill mine. The rocks are not tightly compressed into small cross folds such as are present at the Parnell Hill and Parker Hill properties but are slightly warped where exposed in the openings east of the mine. Mineralization is localized near the top of the sandstone member at its

contact with the overlying shale. At the mine a series of steplike mineralized fractures striking N.8°E. and dipping 65° to 70°W. offset the hanging-wall sandstone, which is mineralized but has been left to hold the overlying shale, and extend north across several sandstone beds to the footwall. Along nearly every fracture the east side has been offset 2 to 5 in. north with respect to the west side. The fractures extend to the bottom of the mine, which has been sunk to a depth of 225 ft. as an open pit 6 to 8 ft. wide and 70 to 80 ft. long. The oreshoots follow these fractures downward. The ore ranges in tenor both laterally and vertically, but generally it is of good grade. Small amounts of stibnite are present. As at Parker Hill mine, ground water from adjacent sandstones found entrance into the mine. At the time of shutdown the mine was about 125 ft. below ground-water level, which is approximately at the level of the stream that cuts across the ridge west of the mine. The flow of water is estimated at between 400 and 600 gal. per hour.

Prospects

Hudgins Prospect.—The Hudgins prospect, S.½, SW.¼, sec. 9, T.7S., R.26W., has a shaft 30 ft. deep in mineralized Jackfork sandstone a short distance east of a cross fault which places the Jackfork across the faulted end of the 300-ft. sandstone of the Stanley shale. The strike of the sandstone is N.83°W. and the dip is 73°S. Mineralization is in fractures striking N.8°W. Power is supplied by a steam boiler, and because of lack of water during the summer months no active work has been done since June, 1934. A 24-tube retort was constructed in June but has not yet been put into operation.

Russell Prospect.—The Russell prospect is in the fractional 40-acre tract adjoining the SW.¼, SW.¼, sec. 6, T.7S., R.25W., on the west end of Parnell Hill (see Fig. 3). Mineralization occurs in cross fractures at the top of the sandstone member at its contact with overlying shale. A small one-tube retort was being erected at the time of this survey.

Yenglin Prospect.—The Yenglin prospect is in the SE.¼, SW.¼, sec. 6, T.7S., R.25W., immediately east of the Parnell Hill property of the Southwestern Quicksilver Co. Part of the geology is shown on Fig. 3. Prospecting is being conducted on the continuation of the 300-ft. sandstone member of the Stanley shale east of the fault that offsets the sandstone member 500 ft. south and 1500 west at a cross fold, where the strike changes from N.65°W. to N.66°E. At the time of this survey a two-tube retort was being built on the sandstone hill north of the prospect. This hill, the eastward continuation of Parnell Hill, is also mineralized.

Summary

Cinnabar was discovered near the southern border of the Ouachita Mountains in southwestern Arkansas in 1930 but was not identified until

June, 1931. The quicksilver district is now known to have an east-west length of about 30 miles and an average width of less than one mile. The principal exposed rocks of the district are shale and sandstone of the Atoka, Jackfork and Stanley formations, of Pennsylvanian age, which aggregate many thousands of feet in thickness. The rocks have been deformed by close folding and thrust faulting and the three formations form several east-northeast trending belts.

Mineralization occurs principally in a sandstone member of the Stanley shale but locally is found at other horizons in the Stanley and in the overlying Jackfork sandstone. All of the cinnabar deposits are in a northward overriding thrust block that is cut by cross faults and is deformed and fractured by cross folding. The cinnabar fills fractures related to the cross folding, and the linear distribution of the ore occurrences is believed to have been due to mineralizing solutions ascending along the thrust fault until they reached fractured sandstones of the Stanley whence they followed these permeable beds toward the surface.

This report covers a 12-mile segment of the district that includes the three mines of the Southwestern Quicksilver Co., from which has come most of the production of the district to date. The Gap Ridge, Parker Hill and Parnell Hill mines are developed to maximum depths of 225 ft., 129 ft. and 187 ft., respectively.

DISCUSSION

(*E. S. Moore presiding*)

N. H. Stearn,* St. Louis, Mo. (written discussion).—I have read with much interest this excellent summary of the geology of the recently discovered quicksilver district in Arkansas. Having been called into the district in September, 1931, by Mr. Leo Yount, the pioneer operator of the district, I have been associated with its development from its infancy. I began systematic geological field work Oct. 3, 1931, with the assistance of L. L. Palmer, as soon as the necessity of making a very detailed geologic and topographic map became apparent. This field work was done by the pacing traverse method, with traverses run at 350-ft. intervals, making four traverses across each 40-acre tract. Transit survey lines checked the traverse locations. Elevations were mapped by altimeters checked by reoccupation of previous observation points, by reference to camp barometer readings, and by level lines. The mapping was done on the scale of 20 in. to the mile, showing the character, attitude and extent of every bedrock exposure. In this detailed manner we mapped 22 square miles along the strike of the cinnabar exposures, 3½ miles east and 8½ miles west of the Little Missouri River.

During the latter half of our survey we were fortunate in securing the services of Dr. J. M. Hansell, the major author of this paper, who two years later returned to the district for the U.S. Geological Survey. The work of the U.S.G.S. has extended our mapped area about two square miles eastward. Having been closely associated with Dr. Hansell during the original work that initiated the structural theories advanced

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* Geological and Geophysical Engineer, W. C. McBride, Inc.

in his paper, I find myself wholly in accord with this general expression of them. Only in relatively minor matters is there divergence of opinion. It may be of interest to review a few points of additional substantiation and a few points of divergence.

For convenience I have given names to two of the sandstone members of the Stanley shale described on page 232 of this paper. The upper 1000 ft. of the Stanley, as here described, is a shaly zone. Below that comes a 100-ft. sandy zone, a 200-ft. shaly zone, and a 300-ft. sandy zone. These three zones comprise a unit formation, markedly expressed topographically, which can be traced the entire length of the district. It has been named the Gap Ridge member of the Stanley shale, from the name of the most important mining development found in that horizon. About 700 ft. stratigraphically below the Gap Ridge member is another sandy zone about 175 ft. thick, which has been named the Parker Hill member, from the name of the most important mining development in that horizon. The Gap Ridge mine, Russell prospect, Parnell Hill mine, and Yenglin prospect as shown on Fig. 2 are all in the Gap Ridge member. The Parker Hill mine and the Old Argentine mine are in the Parker Hill member.

The major thrust fault described on page 235 is postulated on indirect evidence, such as the truncation of the Parker Hill member. This truncation is described as "about halfway between Highway 27 and the Little Missouri River." Additional evidence of this nature is to be found just west of the river, where the same member appears again and is again truncated near the northwest corner of sec. 12, T. 7 S., R. 26 W.

On page 236 the cross folding and fracturing in the area are described, with this added statement: "The evidence as to the age of this buckling relative to the thrusting and cross faulting appears to be conflicting and the small area covered has not served to establish it definitely." A regional study suggests that the thrusting movement was one of considerable duration during which the buckling that accompanied the east-west shortening took place as an intermediate event, so that thrusting occurred both before and after the buckling.

Throughout this paper it is assumed that the massive sandstone formation that lies just north of the thrust-fault plane and which has been overridden by the Stanley shale is of Jackfork age. A study of the stratigraphic section exposed by road cuts along Highway 27 suggests the possibility that it is not Jackfork but a sandstone phase of Upper Atoka, or even a higher formation than the Atoka.

Among the primary minerals associated with the cinnabar, and not mentioned on page 237, is siderite. Quantitatively it is unimportant, but its presence may have bearing on the age of the mineralization.

The age of mineralization is tentatively placed as Upper Cretaceous by this paper. Evidence defining the age accurately is very scarce, but two fragments of evidence suggest late Paleozoic rather than Upper Cretaceous mineralization. First, slickensided surfaces are found, which cut and polish previously mineralized fractures, suggesting mineralization during the period of diastrophic movement; second, the mineral associations have points of resemblance to those of the sulfide deposits in the Ouachita Mountains of Oklahoma, which have been assigned to late Pennsylvanian time by Honess.

With regard to the ore occurrence, the fact that the cinnabar occurs dominantly as fracture fillings makes orebodies very erratic in size, shape and extent. Orebodies are never extensive areally, but seem to persist with depth. The mineralization has produced a concentration of cinnabar which varies in yield up to 200 lb. of metallic mercury per ton of ore. Records of the Southwestern Quicksilver Co. show that the average tenor of all ore run through its plant is 23.4 lb. of mercury per ton of ore. The ratio of ore to rock moved throughout the total development operations is about

1 to 3.5. Thus the average tenor of the rock moved is about 5 lb. of metallic mercury to the ton.

The minor points of divergence briefly mentioned in this comment are treated much more fully in a paper on The Cinnabar Deposits in Southwest Arkansas that I have prepared for publication in *Economic Geology*, as a result of the detailed studies described above. But the major features of the new district are, I believe, excellently described in this paper.

The Magnetite Deposit near Humacao, Puerto Rico

By R. J. Colony,* Member A.I.M.E., and H. A. Meyerhoff,† Associate Member A.I.M.E.

(New York Meeting, February, 1935)

Deposits of iron are widely scattered in the folded Cretaceous rocks and the associated igneous intrusives of Puerto Rico. Most of them are too small for commercial development, but a few have aroused some scientific and economic interest, among them the large body of residual limonite at the west end of the island near Mayagüez[1–6] (Fig. 1) and the mixed hematite and magnetite deposit on the southern slopes of the Sierra de Cayey, about four miles north of Arroyo.[7–9] Neither of these orebodies has been developed, nor have investigations of the widely distributed deposits of magnetite, which include all the remaining occurrences of iron deserving of economic consideration, proceeded beyond the exploratory stage.

With the possible exception of the mixed deposit near Arroyo, the magnetite is directly associated with andesitic and dioritic intrusives, which invade the Cretaceous rock section, and the bulk of it, occurring in calcareous sediments, is clearly of contact-replacement origin. The small deposit on Río Portugües, north of Ponce, is found in a limestone band near its contact with an andesite dike.[10,11] Two deposits of unde-

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1 C. R. Fettke and B. Hubbard: The Limonite Deposits of Mayagüez Mesa, Porto Rico. *Trans.* A.I.M.E. (1919) **61,** 97.

2 G. J. Mitchell: Geology of the Ponce District, Porto Rico. Scientific Survey of Porto Rico and the Virgin Islands (1922) **1,** 292–294.

3 L. A. Smith: World Production and Resources of Chromite. *Trans.* A.I.M.E. (1931) 387.

4 Committee on Mineral Resources of Puerto Rico Rept. No. 1, 2–5. San Juan, P.R., 1933.

5 H. A. Meyerhoff: Geology of Puerto Rico. Univ. of Puerto Rico *Mon.* 1-*B* (1933) 134–136; 146–148.

6 H. A. Meyerhoff: Iron in Puerto Rico. *Rev. de Obras Publicas* de Puerto Rico (1934) **11,** 708–709.

7 C. R. Fettke: Geology of the Humacao District, Porto Rico. Scientific Survey of Porto Rico and the Virgin Islands (1924) **2,** 184.

8 Reference of footnote 4.

9 H. A. Meyerhoff: References of footnote 5, 132; footnote 6, 707–708.

10 G. J. Mitchell: Reference of footnote 2, 292.

11 H. A. Meyerhoff: Reference of footnote 6, 706.

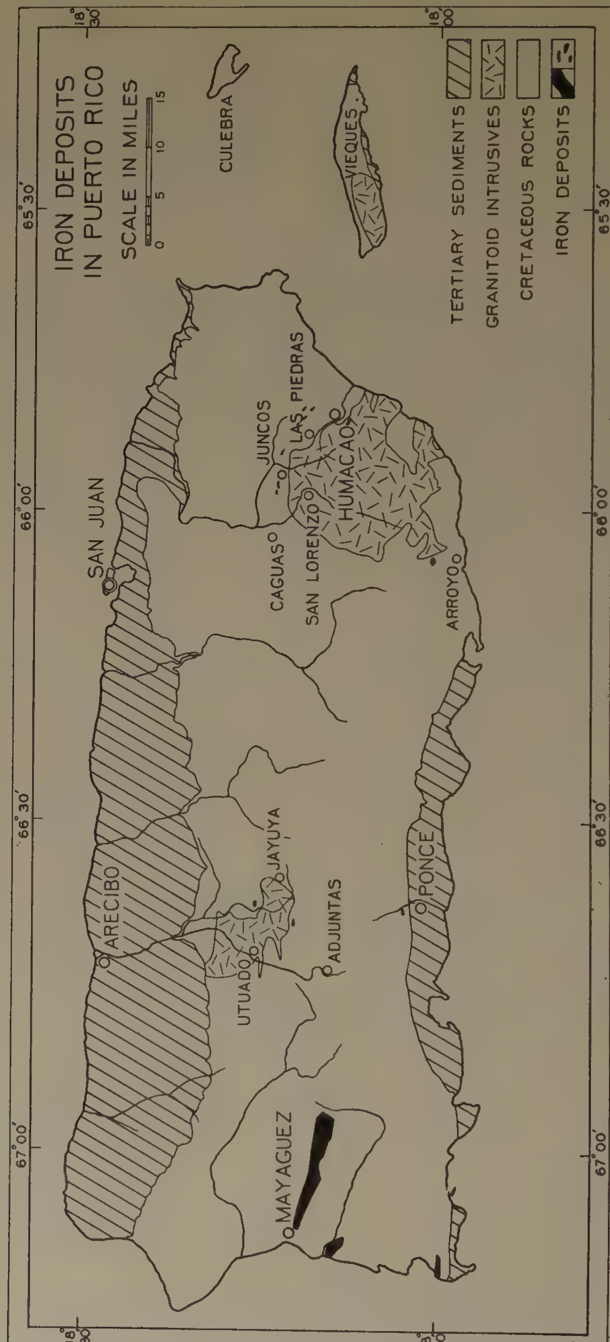

Fig. 1.—Location of iron deposits in Puerto Rico.

termined value flank the Utuado diorite batholith; one, on Monte Morales near Utuado, at the northern margin of the intrusion; the other, on the Alto de la Bandera between Adjuntas and Jayuya, along its southern contact with the Cretaceous sedimentary section. By far the largest series of magnetite deposits is peripheral to the San Lorenzo diorite, which outcrops over 180 square miles in southeastern Puerto Rico and extends to the neighboring island of Vieques. A band of stratified tuffs, shales and thin limestones roughly parallels the northern edge of this intrusive, and contact phenomena are conspicuous along the entire length of the belt, a matter of 20 miles in Puerto Rico, and more than 50 if its extension into Vieques is taken into account.

Within this contact zone there are more than 20 bodies of magnetite, all of which occur in the calcareous strata, and several of the deposits associated with the two thickest limestone horizons are of moderate size and of excellent quality. They have attracted some attention, and 30 years ago, shortly after the American occupation of Puerto Rico, they were studied carefully; but plans made for their exploitation never materialized. Satisfactory royalties could not then be arranged with the property owners, and the engineering reports diverged widely on tonnage estimates. Finally, when the control of the company changed hands, the project was allowed to lapse, and it has never been revived. In 1932, shortly after its organization, the Committee on the Mineral Resources of Puerto Rico made a brief examination of the more important magnetite deposits, with the cooperation of F. W. Lee of the Bureau of Mines. In connection with the investigation, a cursory field study was made[12] of a deposit south of Humacao at the eastern end of the belt, and, in contrast with the geographically associated bodies of magnetite, it was found to be a deposit of magmatic type, with features of sufficient interest to warrant a study apart from the routine classification accorded the other deposits.

Geology of Humacao District

Humacao, the largest town in eastern Puerto Rico, is on a broad alluvial plain, which overlaps the northeastern corner of the San Lorenzo batholith. The iron crops out on the ridge that forms the southern boundary of the alluvial flat, about one mile south of the town and less than one-half mile west of the highway to Yabucoa. It lies some 500 yd. south of the Roig sugar mill (Central Ejemplo) and is easily accessible from the cart roads that thread the adjacent cane fields. The ridge rises abruptly, though somewhat irregularly, above the alluvium to an approximate elevation of 600 ft., and it ascends with similar abruptness

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[12] By W. D. Noble and H. A. Meyerhoff, respectively secretary and geologist of the Committee.

above the higher rolling country to the south. It strikes east and west, disappearing toward the east in the broadening alluvial plain, and merging about a mile to the west with the elevated surface of the Sierra de Cayey upland.

It is not, however, a normal spur protruding from the upland, for it differs from the many neighboring spurs in its comparative isolation and in its length. The linear trend of its relatively level crest suggests a sedimentary structural control such as characterizes the magnetite hills in the sedimentary belt to the north and west. The suggestion is misleading, for the ridge, like the other hills in the region, is composed of massive, granitoid igneous rock, in which the elements of structural control are entirely lacking. Its topographic prominence is due, none the less, to differential weathering and erosion; for the ridge coincides with the areal limits of the magnetite, and its prominence reflects the slow decomposition of the iron oxide, in comparison with the rapid partial decomposition and torrential wash of the normal igneous materials on every side. The phenomenon, indeed, is the usual one in Puerto Rico, where the rate of weathering and erosion is determined in large part by the relative solubilities of the rock-forming minerals. For this reason the iron deposits generally produce conspicuous topographic forms wherever they are exposed to the direct action of the atmosphere and rain.

General Geologic Setting.—The general geologic setting of the region surrounding the Humacao deposit is dominated by the San Lorenzo batholith (Fig. 2).[13] The portion of the batholithic intrusion that outcrops on the Puerto Rican mainland is roughly rectangular in shape, with an axis of elongation that trends northwest-southeast, in general conformance with the orogenic structures of the Cretaceous rocks. The intrusive itself is a medium to moderately coarse granitoid rock with the mineralogic composition of a quartz diorite. The quartz, however, is a variable component, and there are many places within the area of outcrop in which the rock might more appropriately be classified as diorite. Fettke has noted other variations, wherein the normal plagioclase—usually andesine or labradorite—becomes subordinate to the accessory orthoclase, and the rock assumes the aspect of a hornblende granite; or wherein augite takes the place of the typical dark brown-green hornblende. Regional differentiation within fairly broad mineralogic, yet relatively narrow chemical limits, is thus a common feature of the intrusive, but the extreme variation that led to the differentiation of the Humacao iron deposit is distinctly exceptional to the general range.

San Lorenzo Batholith.—The San Lorenz batholith forms the southeastern shore line of Puerto Rico, extending from the mouth of Rio Humacao, on Vieques Passage, to the port of Patillas on the Caribbean.

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[13] C. R. Fettke: Reference of footnote 7, 153–161.

The front that faces the sea is broken by many alluvial re-entrants like the one at Humacao, and its continuity is further interrupted by two series of slightly younger granitoid rocks, which Fettke has named, in

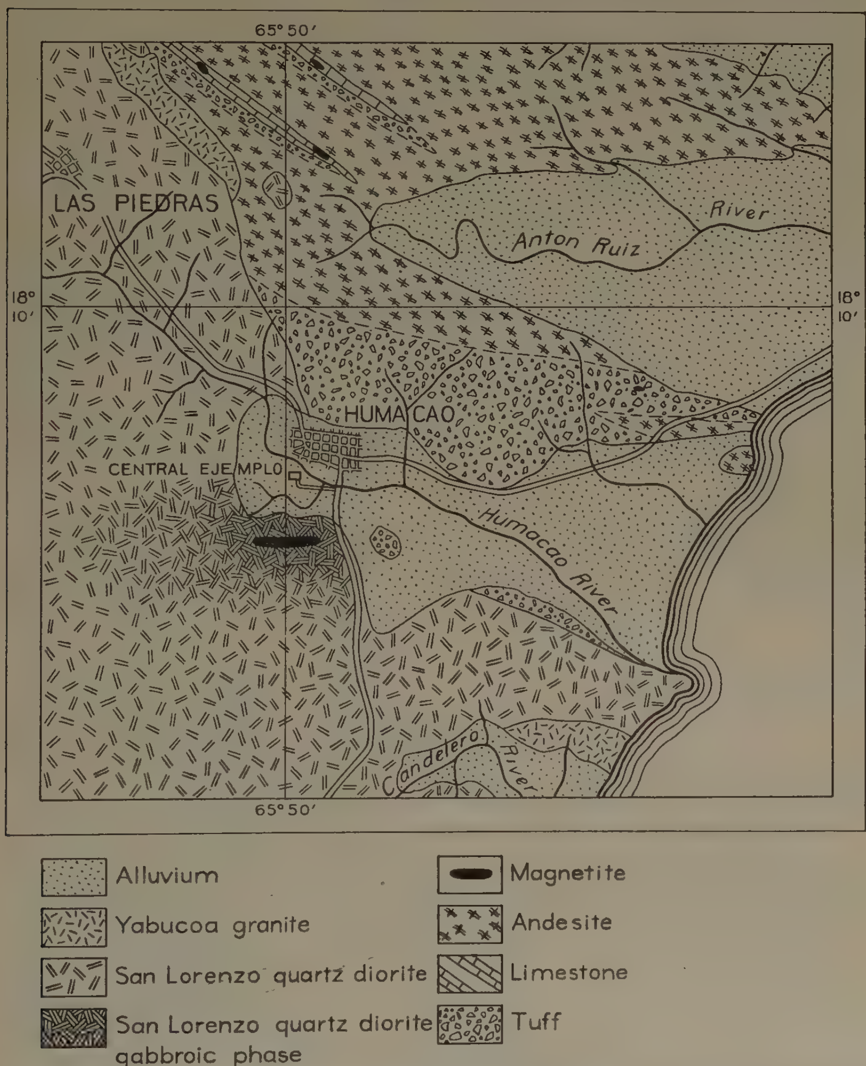

Fig. 2.—Location of magnetite deposit near Humacao; map modified after Fettke.

the order of their intrusion, the Yabucao granite and the Patillas quartz monzonite.[14] Both form a series of isolated stocks and apophyses situated at, or near, the margins of the batholith. The granite is char-

[14] C. R. Fettke: Reference of footnote 7, 159–163.

acterized by a coarse texture and an almost complete absence of ferromagnesian components. In some localities the quartz and orthoclase are micrographically intergrown; in others microperthitic intergrowths of orthoclase and plagioclase are found. There are no exposures of Yabucoa granite in the immediate vicinity of the Humacao ridge; the nearest lie three miles to the south and east, and another isolated exposure is about four miles to the north. Occurrences of the quartz monzonite are considerably more remote, and for this reason the soda alaskite-aplite dikes which cut the rocks associated with the magnetite deposit are believed to have been connected either with the granitic phase of post-San Lorenzo intrusion, or with the gabbroic anorthosite-pyroxenite differentiate series, as an end-stage concentration residuum.

Intruded Stratigraphic Section.—The granitoid intrusives have invaded a thick section of Upper Cretaceous rocks, which are dominantly volcanic in character. They are exposed in the hills that bound the Humacao alluvial plain on the north, and extend from this point to the north coast of the island without interruption, save for a few dioritic stocks, apophyses and dikes, not to mention the recent fluvial sediments which locally bury them.

The section is approximately 9000 ft. thick in this part of Puerto Rico.[15] It consists of 5000 ft. of massive tuffs at the base, followed upward by a stratified series of tuffs, ash, ashy shales and two interbedded limestone formations (Fig. 3). Andesite and felsite flows and sills are commonly intercalated with the stratified formations, and at one horizon they reach a thickness of 500 ft. or more. Their maximum development is attained in the area lying immediately to the north and east of Humacao. Dikes and irregular masses of andesite porphyry cut the section but in turn are truncated by the San Lorenzo diorite and the younger granitoid intrusives.

In the neighborhood of Humacao the stratigraphic succession is far from clear. The locality is near an Upper Cretaceous volcanic vent, from which flows and shallow intrusives were promiscuously introduced into the section at every horizon. During the closing stages of eruptive activity, vigorous folding and some thrust faulting occurred, which was immediately succeeded by the series of magmatic invasions already described. Contact metamorphism obscured the sedimentary structures and converted the flows and pyroclastic materials to an aggregate of chloritized rock, in which flow structure and undestroyed fragmental textures supply occasional clues regarding the nature of the original materials; but in some cases even the microscope cannot penetrate the metamorphic disguises the formations have assumed. Only the lime-

[15] H. A. Meyerhoff and I. F. Smith: Geology of the Fajardo District, Porto Rico. Scientific Survey of Porto Rico and the Virgin Islands (1931) **2**, 268–269.

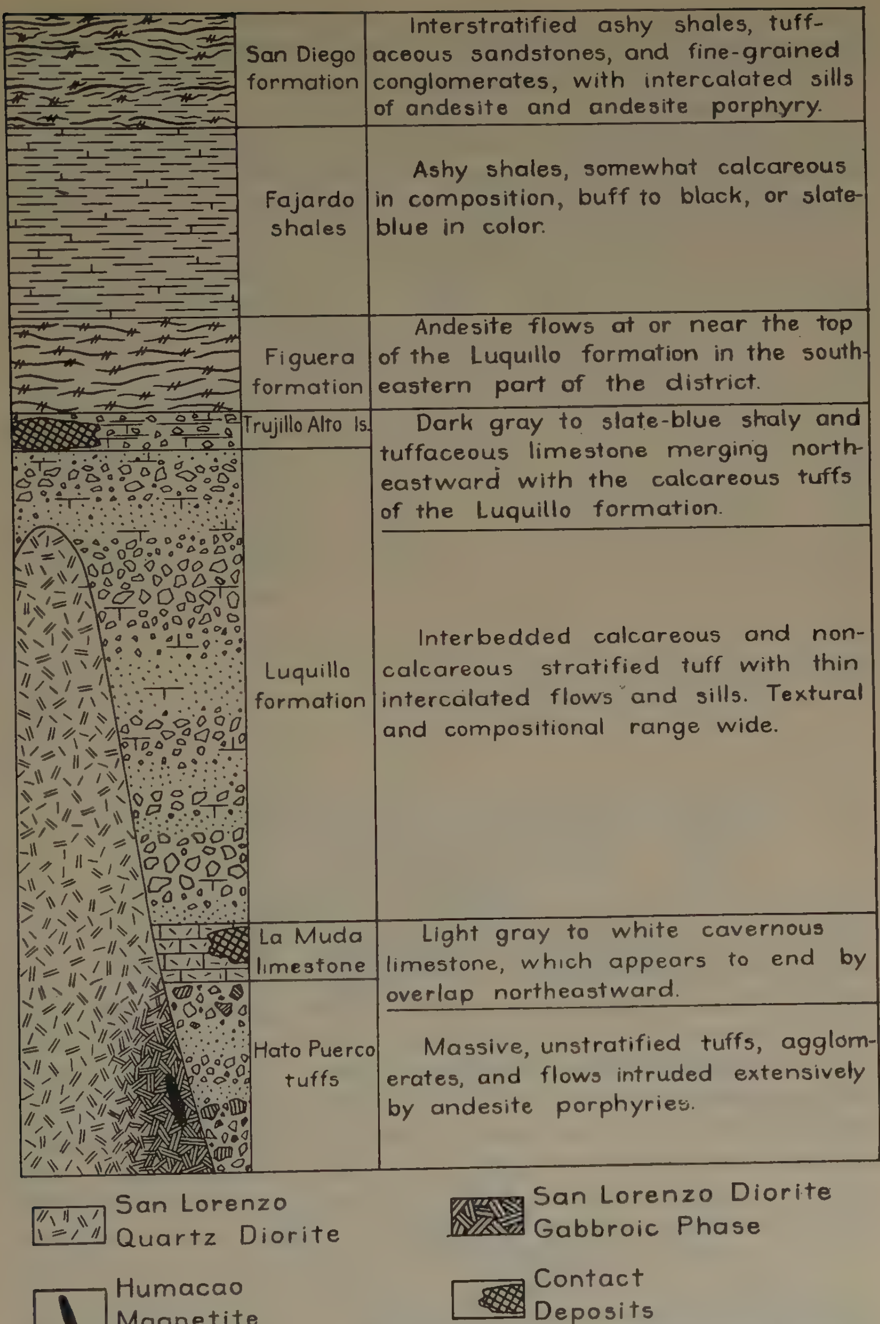

FIG. 3.—COLUMNAR SECTION IN EASTERN PUERTO RICO. STRATIGRAPHIC RANGE OF SAN LORENZO BATHOLITH.

stones and certain of the shales have retained their identity, despite the silicification of the latter and extensive silication and mineralization of the former immediately north of the intrusive contact.

Contact Ores.—Although the Upper Cretaceous section is not directly related to the problem of the Humacao magnetite, it acquires pertinence because of the fact that magnetic iron ore was also introduced into the limestones at several points along the northwestern and northeastern

TABLE 1.—*Analyses of Contact Ores*

	San Miguel Iron Ore, Las Piedras, P.R.[a], Per Cent	Esperanza Ore near Juncos, P.R.[b], Per Cent
Fe_2O_3	72.500	73.30
FeO	19.671	17.82
SiO_2	5.300	4.82
Al_2O_3	tr.	1.22
CaO	0.271	0.30
MgO	0.402	0.35
P_2O_5	0.056	0.054
S	0.008	0.03
CO_2	tr.	0.00
Cu	0.000	tr.
H_2O (combined)	1.790	1.83
H_2O (free)		0.17
	99.998	99.894
Metallic iron	66.05	65.17

[a] Analysis by Pattison and Stead, Middlesborough, England.
[b] Analysis by Edward Riley, London.

margins of the San Lorenzo batholith.[16–19] The sedimentary members come into direct association with the diorite on these two fronts and, notwithstanding a rough parallellism between their strike and the trend of the contact, the intrusive cuts irregularly across the strike, penetrating now one formation, now another (Fig. 3). Where the diorite impinges upon the limestone, the latter has been altered to an aggregate of silicates, including garnet, epidote, chlorite, amphibole, pyroxene and talc; but magnetite does not appear, except in minor quantities with hematite, short of a mile from the actual contact in any of the orebodies. The stratigraphic distance between iron and intrusive, as measured across the dip of the formations, is in most instances considerably less, and in one

[16] C. R. Fettke: Reference of footnote 7, 184–194.
[17] C. R. Fettke: Magnetite Deposits of Eastern Porto Rico. *Trans.* A.I.M.E. (1924) **70**, 1024–1042.
[18] H. A. Meyerhoff and I. F. Smith: Reference of footnote 15, 317.
[19] H. A. Meyerhoff: Reference of footnote 6, 705–706.

of the deposits in Barrio Collores de Piedras, the mineralized limestone is separated from the intrusive by as little as 600 or 700 ft. of tuff.

The magnetite of contact origin makes its first appearance in the range of hills south of the Caguas-Humacao highway about four miles east of Caguas, where it forms a broken chain of deposits stretching eastward for 12 miles along the border of the batholith. At the eastern extremity of the magnetite belt, two parallel series have been formed in the two limestone horizons; but the more northerly band, best developed near the village of Torres, is comparatively remote from the intrusive, and the mineralization is spotty and limited in extent. The

TABLE 2.—*Analyses of Humacao Samples*

	Samples[a]				
	4	1	2	3	5
SiO_2	75.38				
Al_2O_3	14.49				
Fe_2O_3	0.49	12.66	20.22	20.82	78.83
FeO	0.11				
MgO	0.14				
CaO	1.45				
Na_2O	7.17				
K_2O	0.06				
H_2O	0.56				
TiO_2		0.93	1.63	2.36	5.35

[a] R. B. Ellestad, analyst.

4. Soda alaskite-aplite dikes, cutting the rock associated with the ore.
1. Gabbroic anorthosite, base of magnetite ridge.
2. Hornblendic gabbro, 150 ft. above base of ridge.
3. Hornblendic pyroxenite, 250 ft. above base of ridge.
5. Ore: magnetiferous pyroxenite, 400 ft. above base of ridge.

easternmost of the contact deposits lies less than 4 miles due north of the Humacao occurrence; and, despite radical genetic differences in their modes of origin and the inevitable contrasts in their mineralogy and chemistry, the two types are closely related in the time of their formation, and presumably they drew upon the same magmatic sources for their iron. Unfortunately it is impossible to compare the two varieties chemically, for only two complete analyses of the contact ore are available (Table 1), and the analyses of the Humacao ore are partial (Table 2). One outstanding point of difference is the absence of titanium in the contact samples.

Local Geologic Features.—The Humacao orebody occupies a position close to the northern edge of the batholithic intrusive (Fig. 2), and the contact with the Cretaceous rocks presumably lies a short distance

beyond the base of the ridge, buried beneath the Recent alluvium. A scant half mile to the east, an isolated hill of metamorphosed tuff rises from the fluvial debris, separated from the diorite exposures on the Yabucoa road by 250 yd. of river sediments. Still farther east the hills that fringe the Humacao plain are faced by a thin band of altered tuffs, which preserve some vestige of an original sedimentary habit. Like all the Cretaceous strata immediately northeast of the batholith, they strike west-northwest (N.57°W.) and dip moderately northeastward into the broad synclinal fold that separates the massive igneous rocks of the Sierra de Cayey upland from the highly folded and compressed sediments of the Luquillo Mountains. The contact is also exposed on the outskirts of Humacao, on the northern side of the valley.

At the latter point, 1¼ miles north of the magnetite deposit, the quartz diorite is normal, save for conspicuous chloritization, which gives it a strong greenish tint. South of the magnetite ridge, within ¾ mile of the deposit, the intrusive is also normal, but it is notably deficient in quartz. From both these localities the diorite becomes increasingly gabbroic toward the iron deposit, and to the south the numerous exposures along the Yabucoa road offer an excellent opportunity to study the progressive changes. Quartz completely disappears, and augite becomes first an accessory and then the dominant ferromagnesian mineral, while the hornblende becomes less conspicuous. The extinction angles of the plagioclase, in sections perpendicular to the albite twinning, likewise increase from 26° to 34°, in response to a moderate increase in the calcium content of the feldspar.

At the magnetite ridge the best exposures are on the northern side, for in this direction the relief between ridge crest and valley floor is greater, and the steeper slope produced has proved less hospitable to vegetation. The exposures have undergone considerable weathering, but not enough to obscure the identity of the minerals or the textural features of the intrusive, which becomes increasingly coarse toward the orebody. Gullies provide a few fresh exposures, from which satisfactory specimens were obtained. Prominent in the dark-hued and weathered gabbroic country rock are a few lenslike alaskite-aplite dikes, the freshness and light color of which provide a striking element of contrast to their more somber lithologic associates. The dikes are irregular both in trend and in thickness, but none of those seen exceeds 20 in. from wall to wall. Most of them exhibit gentle to moderate inclinations and several were observed to intersect.

The mineralogic changes that occur within the intrusive are progressive up the ridge slope to an approximate elevation of 400 ft. above the plain. At this level three exploratory tunnels, now partly or completely choked by debris, penetrate the hill, and in the most westerly excavation the iron ore was encountered about 20 ft. from the surface. According to

W. D. Noble, the magnetite was found within 30 ft. of the surface in the other two tunnels, and one of them was extended 90 ft. through ore before operations ceased. Above this level magnetite float becomes increasingly prominent on the surface, but the ridge was not explored to its summit, and no surface ore was observed *in situ*. A higher tunnel, 80 ft. below the crest, was not seen, and two of the other three openings were located with difficulty amid a 33-year accumulation of debris and vegetation.

Petrography

The transition from the normal diorite to gabbro exhibited by the rocks along the Yabucoa road is carried on at an accelerated tempo in the exposures on the north side of the magnetite ridge. At the base of the latter the rock is essentially a gabbroic anorthosite; 150 ft. higher the anorthosite gives way to a gabbro, and this in turn gives way to a hornblendic pyroxenite 250 ft. above the base. The "iron" ridge itself, at an elevation of 400 ft., is a richly magnetiferous pyroxenite, more or less hornblendic.

General Petrographic Description

Sample No. 1, collected near the base of the "iron" ridge 1 km. south of Central Ejemplo, is a gabbroic anorthosite. Básic plagioclase, consisting of both labradorite ($Ab_{35}An_{65}$) and bytownite ($Ab_{25}An_{75}$), comprises 70 per cent of the rock. The plagioclase, which is extensively twinned, is perfectly fresh except for the erratic distribution of small, irregular, ragged zoisitized patches, from which tiny stringers may extend for short distances along cleavage and fracture directions in the plagioclase. It is idiomorphic to hypidiomorphic in form, and in general the ferromagnesian components are interstitial with respect to it, although there is an occasional tendency towards an ophitic development.

The dominant ferromagnesian component is light-colored hornblende containing remnants of colorless pyroxene, from which most of the hornblende was derived. Very small amounts of chlorite, epidote, zoisite, calcite and biotite have developed from the hornblende as additional and further modification products of the changes that affected the original pyroxene. The hornblende, including the residual patches of original pyroxene, comprises about 25 per cent of the rock. It is more strongly colored than the hornblende in the ore itself, which is but faintly green in thin section, and which is crowded with black inclusions.

Ilmenitic magnetite, which constitutes 3 or 4 per cent of the rock, is distributed in both euhedral and subhedral crystals, for the greater part in the hornblende, but some of it is present in the feldspar also. Where the magnetite crystals are included in the basic plagioclase feldspar, there is commonly an aggregate of zoisite surrounding them and separating

them from the enclosing feldspar. Mixed aggregates of zoisite and epidote also occur as alteration products of the hornblende, especially in connection with crystals of magnetite. Figs. 4 and 5*A* illustrate some of these features. Where the magnetite is not connected with, or enveloped by, zoisite-epidote aggregates, it is usually euhedral. But when associated with zoisitized areas, it is commonly subhedral and even anhedral, with ragged boundaries and attached stringers, as though the

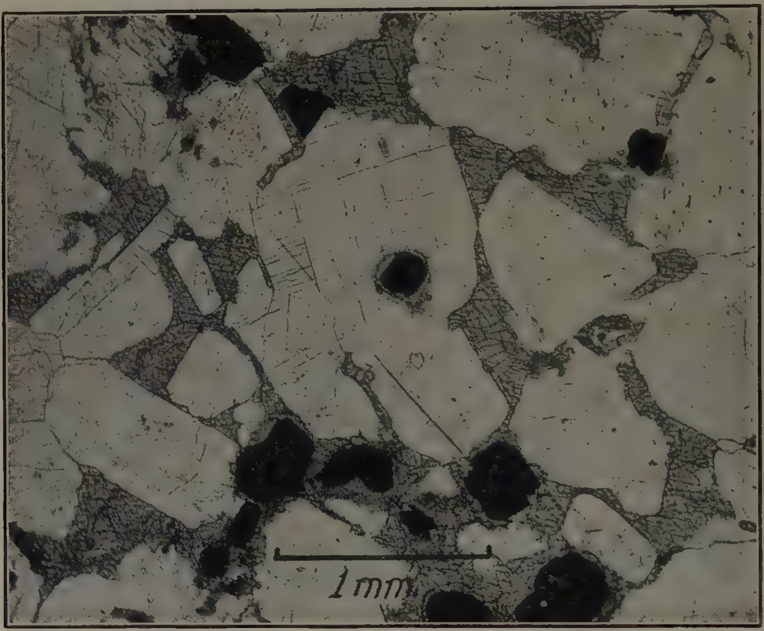

FIG. 4.—SPECIMEN 1(*a*). GABBROIC-ANORTHOSITE, ORDINARY LIGHT. Showing hornblende interstitial to plagioclase, and euhedral and subhedral grains of magnetite distributed chiefly in hornblende. Magnetite grain in plagioclase crystal is surrounded by narrow zoisitized zone.

conditions responsible for the production of the zoisite aggregates were likewise responsible for some slight attack on the magnetite itself.

The plagioclase contains both crystal and vacuole inclusions, generally haphazard in arrangement; occasionally there are black, hairlike, acicular inclusions that exhibit orientation, and these are judged to be rutile. Among the crystal inclusions are numerous minute black grains, probably magnetite; minute prisms of apatite; beautifully developed, faintly greenish and slightly pleochroic crystals, judged to be hornblende, which themselves contain inclusions. The inclusions within inclusions consist of black grains, which in some cases are wholly included within the tiny crystals of hornblende, and in other instances lie partly within and partly without the hornblende crystals. There are also translucent, brown, nonpleochroic crystal scales, which, despite their evident monoclinic

form, were not determinable. Groups and bands of minute vacuole inclusions are present in the plagioclase, and most of the vacuoles contain liquid, as well as bubbles which are in constant motion (Fig. 6, *B* and *C*). In addition to the components mentioned, the rock contains very small amounts of titanite and green spinel as negligible minor accessories.

The total amount of iron in the rock, reported as ferric oxide, is 12.66 per cent; the titania is 0.93 per cent. It is difficult to say what proportion of iron may be contained in the crystals of magnetite, for

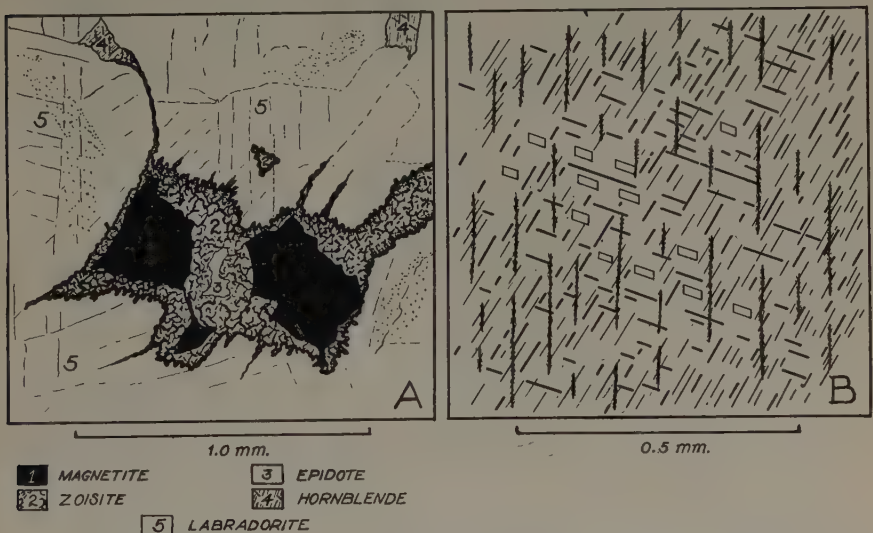

FIG. 5.—SPECIMEN 1, GABBROIC-ANORTHOSITE, ORDINARY LIGHT.
A. Slight zoisitization of plagioclase (labradorite), and anhedral grains of magnetite associated with zoisitized area. A little epidote has developed also.
B. "Schiller" structure in hornblende in ore.

some of the hornblende in the samples carries so much included magnetite that it is strongly attracted by the magnet. Moreover, the hornblende contains iron as a part of its own make-up; hence it is not possible to state what amount of iron may be referred to the magnetite in any of the samples.

Specimen No. 2, taken on the magnetite ridge about 150 ft. above the base, is a hornblendic gabbro. The plagioclase content has fallen to 25 per cent, the ferromagnesian content has risen to 65 per cent, and there is approximately 8 or 9 per cent of ilmenitic magnetite in the rock.

The plagioclase is a basic labradorite or bytownite ($Ab_{25}An_{75}$). The greater part of it is anhedral and not altered, except for minute ragged patches of aggregate zoisite and a tendency to slight zoisitization along the margins. The ferromagnesian components consist of colorless pyroxene, which makes up about 30 per cent of the rock, and olive-green hornblende, which is present to the extent of about 35 per cent. Very

small amounts of apatite and titanite form the minor accessory minerals.

The colorless pyroxene has a large optic angle, a birefringence of approximately 0.025 and a maximum extinction angle of 46°. It is inferred to be colorless augite. It occurs both as unaltered anhedral crystals and as cores, or remnant patches, in the hornblende. The hornblende is moderately strongly colored, greenish along Z and yellowish green along X. Some of it has been derived from the pyroxene, because it, too, contains cores and ragged patches of pyroxene as "hold-

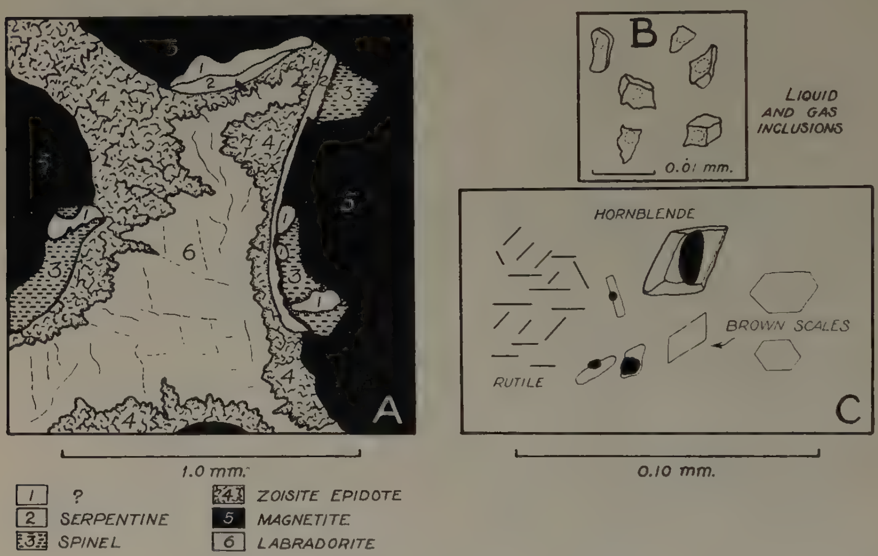

FIG. 6.—PLAGIOCLASE AND INCLUSIONS.

A. Zoisitized remnant of plagioclase in ore, specimen 5(*b*-1) ordinary light. Magnetite contains a little spinel, in which minute grains of brilliantly polarizing mineral mentioned (olivine or diopside?) are included. From the latter a little serpentine has developed.

B and *C* represent inclusions in plagioclase of gabbroic-anorthosite, specimen 1.

over" remnants. Perhaps all of it may have been so derived; but many of the hornblende crystals contain no trace of pyroxene remnants, and they exhibit such sharply unit polarization without the slightest aggregate effect that they have all the aspects of hornblende crystallized directly as such from the magma. It is reasonable to suppose that, during crystallization, a condition of unstable equilibrium was reached with respect to pyroxene, which was in part transformed to hornblende, while the same magmatic condition permitted direct crystallization of additional hornblende from the magma.

A few of the hornblende crystals contain thin, black and closely parallel inclusions oriented in two directions; one set is parallel to the pinacoidal plane and the other is believed to be oriented parallel to the

base. These inclusions are of minor importance in this specimen, but in specimen 3, secured nearer the top of the magnetite ridge, the black inclusions in the hornblende become a prominent feature.

The total iron in the rock, Fe_2O_3, is 20.22 per cent, and the amount of titania is 1.63 per cent. The greater part of the magnetite is euhedral and subhedral. Some grains show slight encroachment on the associated hornblende, and occasional grains are somewhat ragged, exhibiting

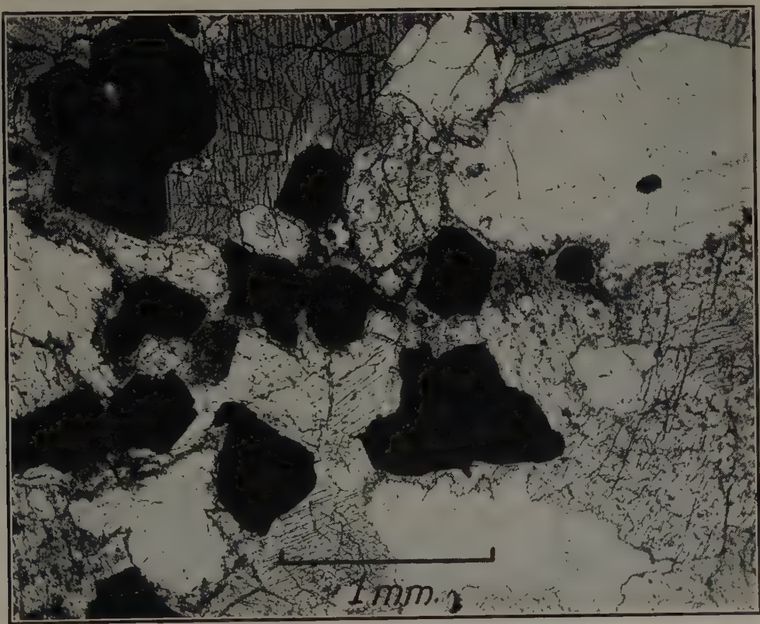

FIG. 7.—HORNBLENDIC GABBRO, SPECIMEN 2(*b*), ORDINARY LIGHT.
Showing labradorite, hornblende, pyroxene and magnetite. Labradorite exhibits slightly zoisitized margins where in contact with ferromagnesians. Some magnetite crystals show slightly transgressive relations, and remnants or cores of pyroxeue appear in some hornblende crystals.

attached stringers and a transecting behavior, especially where the magnetite is associated with, or surrounded by, areas of aggregate zoisite-epidote as is common when it is included in the feldspar. Fig. 7 shows the general habit of the rock.

Specimen No. 3 was obtained about 200 ft. below the summit of the magnetite ridge, and 200 or 250 ft. above the base. The feldspar at this point has almost completely disappeared and the ferromagnesian components have increased correspondingly in amount. The texture of the rock is very coarse, some of the crystals being more than 3 cm. Pyroxene and hornblende together constitute over 85 per cent of the rock, and ilmenitic magnetite makes up from 10 to 12 per cent of it; the rest is composed of small quantities of apatite, titanite, basic plagioclase (which is almost wholly altered to aggregates of zoisite, epidote and sericite),

and green spinel, which comprise the *ensemble* of small minor accessory minerals; alteration aggregates made up of zoisite, sericite, epidote and chlorite are present in very small amounts.

The rock is a hornblendic pyroxenite and is judged to be a differentiate of the gabbro. Owing to the extremely coarse texture, it is difficult to determine the proportions between the pyroxene and hornblende, for the amounts vary too much in the several thin sections. In one section hornblende is dominant; in another, pyroxene; while in a third section the proportions are still different.

The pyroxene is the same colorless variety as that in the other specimens. The hornblende appears to be slightly more sodic, because some crystals have bluish green margins and irregular, splotchy, bluish green patches within them, with occasional areas that are decidedly bluish green and fibrous. Much of it has clearly developed from the pyroxene.

Inclusions in Hornblende

The hornblende, both in this specimen and in the ore itself, is characterized by black inclusions that are judged to be magnetite because fragments of the hornblende are attracted by a magnet. These are so prominent in some of the crystals as to give the hornblende a "schiller" structure. The inclusions consist of lines of closely parallel, delicate black needles or very thin plates and rods, oriented in two directions, and intersecting. One set is arranged parallel to the pinacoidal plane; in crystals cut parallel to the base and showing intersecting prismatic cleavage cracks, the black lines of inclusions bisect the angles between the two cleavage directions. Another set of the inclusions seems to be oriented parallel to the base. The two sets intersect at angles that vary according to the orientation of the crystals in the thin section. There is, in addition, an irregular development of black dust that seems to favor fracture directions in the hornblende, and occasional groups of thin, brown, translucent scales, like those frequently found in hypersthene, were also noted.

Descriptions of similar inclusions in hornblende appearing in the literature indicate that this structural condition is not unusual but, on the contrary, is fairly common in gabbros and related rock species. The senior author has previously observed the same structures in the hornblende of gabbroic rocks from other localities.

The term *schillerfels* was used by von Raumer[20] for a group of rocks whose minerals exhibited an irridescent effect and contained Werner's *schillerspar*. The concept of "schillerization" as a *process* that might

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[20] K. von Raumer: Das Gebirge Nieder-Schlesiens, der Grafschaft Glatz und eines Theils von Böhmen und der Ober-Lausitz, 40. Berlin, 1819.

affect minerals of different species was first set forth by J. W. Judd.[21] Although Judd did not include hornblende in the list of minerals that might be so affected, he mentions that Breithaupt, Haidinger and Häuy had recognized the fact that many different minerals may exhibit the peculiar reflection of schillerspar. F. W. Hutton,[22] and J. Austen Bancroft[23] and C. Chelius[24] refer directly to schiller structure in hornblende. There are other references[25–30] to inclusions in hornblende, but the structures were not definitely called "schiller" by the authors.

In the Puerto Rican specimens under examination, the structure is of interest because it is confined almost wholly to the hornblende. It is definitely not a hold-over structure from the augite, for the augite has very few inclusions. Occasional small groups of oriented black needles are sparsely distributed in the unmodified augite crystals, but they are so insignificant that it is improbable that the numerous inclusions in the hornblende could have been originally in the augite from which the hornblende was apparently derived. Moreover, the augite, to judge from its lack of color, contains very little iron, whereas the hornblende is distinctly ferruginous. The change from augite to hornblende was evidently not a simple equilibrium change, but a change that involved the addition of iron, and during which the newly formed hornblende was supersaturated with iron to such a degree that much of it separated as magnetite within the crystals and was oriented along crystal planes. Fig. 8 illustrates the schiller structure in the hornblende, together with the general character of the rock.

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[21] J. W. Judd: On the Tertiary and Older Peridotites of Scotland. *Quarterly Jnl.* Geol. Soc. (London) (1885) **41,** 383.

[22] F. W. Hutton: On a Hornblende-Biotite Rock from Dusky Sound, New Zealand. *Quarterly Jnl.* Geol. Soc. (London) (1888) **44,** 746.

[23] J. A. Bancroft: Geology of the Coast and Islands between the Strait of Georgia and Queen Charlotte Sound, B.C. Canadian Dept. Mines *Mem.* 23, (1913) 97.

[24] C. Chelius: Referred to by H. Rosenbusch: Mikroskopische Physiographie der Mineralien und Gesteine, **2,** 333, 1907.

[25] G. H. Williams: Peridotites near Peekskill, N. Y. *Amer. Jnl. S.* (1886) [3] **31,** 32, 38.

[26] W. H. Hobbs: On Two New Occurrences of the "Cortlandt Series" of Rocks within the State of Connecticut. *Festschrift von Harry Rosenbusch* (1906) 25–48, 34, 40, 45.

[27] G. S. Rogers: Geology of the Cortlandt Series and Its Emery Deposits. *Ann.* N. Y. Acad. Sci. (1911) **21,** 11–86.

[28] H. Rosenbusch (E. A. Wülfing and O. Mügge): Mikroskopische Physiographie der Mineralien and Gesteins, 531. 1926.

[29] F. Zirkel: Die Mikroskopische Beschaffenheit der Mineralien und Gesteine. 1886.

[30] A. Cathrein: Ueber die Hornblende von Roda. *Ztsch. f. Kryst. u. Min.* (1887) **9,** 9.

Magnetite, Spinel and Titanite

The rest of the magnetite present in specimen 3 is in part euhedral, in part anhedral; some of the crystals exhibit encroachment relations, especially where the grains are distributed in the plagioclase, which exists in very small amounts in this specimen. In such cases the magnetite is usually associated with, and surrounded by, fine aggregates of zoisite. Green spinel is invariably connected with magnetite, forming

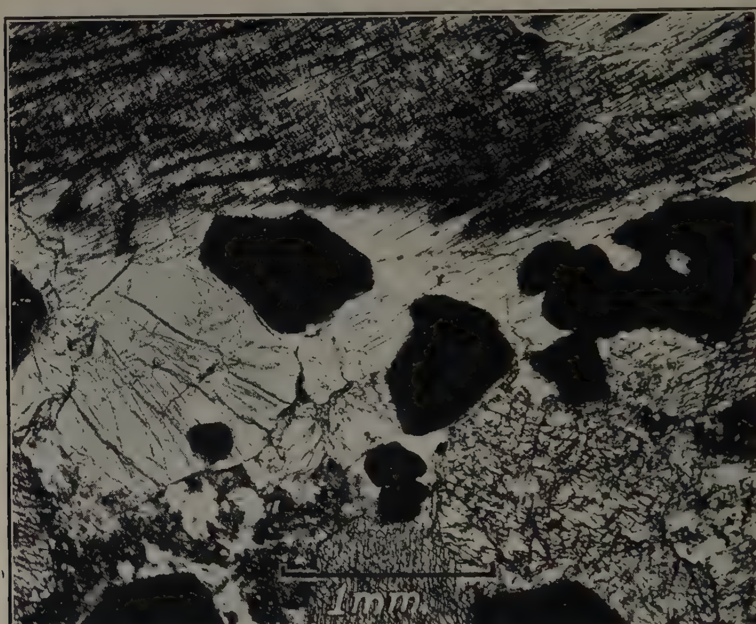

FIG. 8.—PYROXENITE, SPECIMEN 3(*a*-1), ORDINARY LIGHT.
Hornblende is crowded with black inclusions, which impart a "schiller" effect. Pyroxene at extreme left and at lower right contains no black inclusions. Note transgressive habit of magnetite. Portion of hornblende that contains grains of magnetite is clear and free of black inclusions.

part of some of the magnetite grains, but there is very little of it in the rock. A few small anhedral grains of titanite, interstitial with respect to the augite and hornblende, account for a subordinate part of the titanium, but the amount of titanite is so insignificant that by far the greater part of it must be present in the magnetite grains in the form of ilmenite.

The iron content totals 20.82 per cent as Fe_2O_3, which represents iron included in the hornblende as magnetite, combined iron in the hornblende and iron in the magnetite grains; 2.36 per cent of titania is present.

THE ORE (SPECIMEN NO. 5)

Several specimens of rock and ore were collected at the entrance to the tunnel, which is approximately 400 ft. above the base of the ridge. They

are all coarse-textured, highly magnetiferous hornblendic pyroxenite. The pyroxene is the same colorless variety as that in the other specimens, and it exceeds the hornblende in amount. Occasional crystals carry a few fine, black, closely parallel needlelike inclusions, but inclusions are not common in the pyroxene.

The hornblende is lighter colored than that in the other specimens; it varies from light olive-green to faintly yellowish green in its pleochroic behavior, and in many grains the inclusions are so abundant as to give the mineral a marked schiller structure. The inclusions consist of the same closely spaced, intersecting sets of fine black needles, rods and dust which have already been described, together with thin, translucent brown scales (Figs. 5*B* and 8). Prof. Paul F. Kerr made X-ray diffraction patterns of the hornblende from specimens 3 and 5, comparing them with the diffraction pattern of hornblende from Formosa, made at the same time. The patterns are all identical, and it must be concluded that, notwithstanding the color differences mentioned, the hornblende in all of the specimens is essentially the same.

There is very little feldspar in the ore; but samples of what is presumably "rock," which are so richly magnetiferous as to be almost indistinguishable from the "ore," contain a little labradorite, much of which is extensively zoisitized (Fig. 6*A*). The hornblende itself has suffered a little alteration, the products consisting of zoisite, epidote and very small amounts of chlorite and sericite. These mixed aggregates contain zoisite exhibiting characteristic ultra-blue interference colors, and zoisite with gray-white interference colors, the latter having polysynthetic twinning.

Magnetite and Spinel.—Magnetite occurs abundantly in euhedral, subhedral and anhedral grains. None of the specimens of ore collected contains magnetite in massive form; all of it is granular. Many of the anhedral grains are distinctly transgressive; they transect both pyroxene and hornblende and send out little stringers along cleavage cracks, thus affording proof of development subsequent to conversion of the pyroxene to hornblende.

Green spinel is closely associated with the magnetite and evidently is contemporaneous with it, for the spinel occasionally occupies cleavage cracks in the hornblende together with the magnetite and invariably is included in the magnetite crystals.

Most of the spinel is segregated within the magnetite in the form of unoriented, anhedral, more or less ragged unit-grains, which are not a product of "unmixing." According to Osborne,[31] "The presence of spinel is believed to be due to the unmixing of a once homogeneous solid

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[31] F. F. Osborne: Certain Magmatic Titaniferous Iron Ores and Their Origin, II. *Econ. Geol.* (1928) **23**, 906.

solution of spinel in magnetite." Most of the spinel in this ore is not distributed along crystal directions in the magnetite but occurs in individual grains with no orientation whatever, and it is clearly not a product resulting from the unmixing of a solid solution of spinel in magnetite.

Moreover, the magnetite has encroached on many of the spinel grains, with evidence of slight replacement (Figs. 9 and 10). No oriented, fine

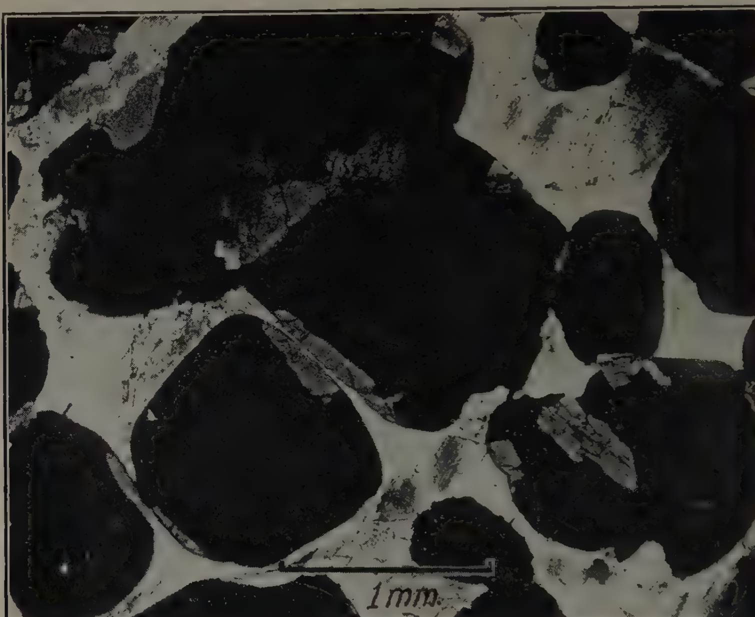

Fig. 9.—The ore, specimen 5, ordinary light.
Showing magnetite and associated spinel distributed in magnetite in form of rough, darker gray patches. Spinel is segregated in grains of magnetite in manner shown, without suggestion of orientation. Lighter "matrix" surrounding magnetite is hornblende, which contains black, dustlike oriented inclusions in spotty distribution.

lamellae of any sort are visible in the magnetite crystals in the thin sections, but in the magnetite of polished surfaces of the ore very fine, oriented and intersecting lamellae were observed, which were judged to be spinel (Fig. 11). They are dark in reflected light, whereas lamellae of both ilmenite and hematite are lighter in color under the same conditions of illumination, prominently so on surfaces etched with hydrochloric acid, That is not true of the exceedingly fine lamellae in the magnetite in the Humacao ore. It is possible, therefore, that a subordinate amount of the spinel may be attributed to unmixing.

Extremely small, rough, colorless and allotriomorphic grains with high relief and brilliant interference colors are included in the spinel as a very minor component. These grains resemble olivine or diopside. They are so insignificant in amount that no further attempt was made to identify them. In a few instances minute quantities of serpentine have

developed from them as a result of the mild attack that later produced the mixed aggregates of zoisite and epidote from the plagioclase and hornblende (Figs. 6*A*, 9 and 10).

Hematite.—A few thin plates larger and longer than the spinel stand out prominently on the etched surfaces of the magnetite. Presumably

FIG. 10.—THE ORE, SPECIMEN 5, ORDINARY LIGHT.
Illustrating segregation of spinel within magnetite, transgressive habit of magnetite and strong suggestion of slight attack by magnetite on spinel.

these, together with tiny, roughly rhombohedral plates, and spots that appear to be oriented, are hematite, which also is thought to be a product of unmixing. The quantity of oriented lamellae and tiny plates is very small, but scarcely a magnetite grain in the ore is completely free of them, and in occasional grains they are abundant.

Ilmenite.—The ilmenite occurs in relatively large plates and grains, and less commonly in the form of globular spots, which have a different reflecting capacity from the much smaller oriented lamellae and scales that were identified as hematite (Fig. 12). All of the ilmenite appears to be distributed in the form illustrated in Fig. 12. There is 5.35 per cent

of titania in the ore specimens analyzed and 78.23 per cent of total iron as Fe_2O_3 (Table 2).

Origin of Ore.—The form, extent and exact relation of the orebody to its enclosing rock have not yet been determined. The concentration of the ore in pyroxenite, which is itself a differentiate of the gabbro, as is the gabbroic anorthosite; the progressive concentration in iron from the

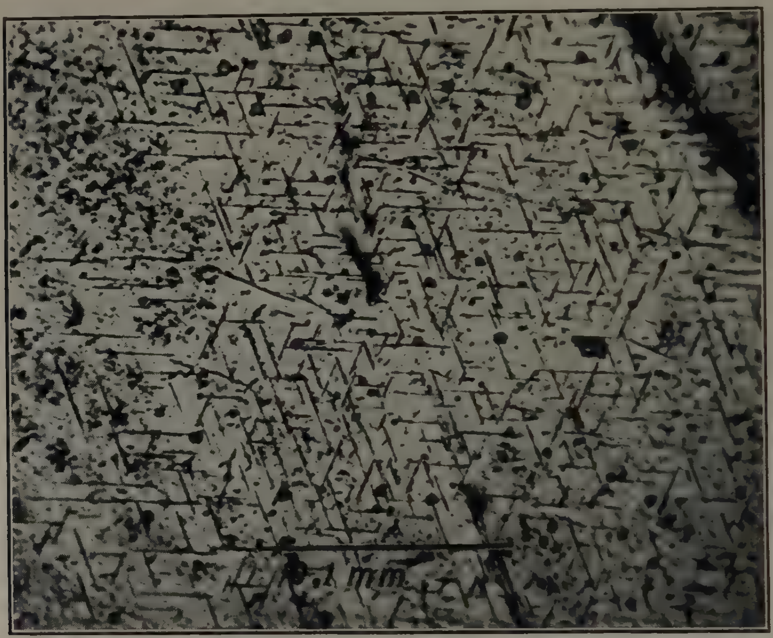

Fig. 11.—The ore, specimen 5. Polished surface lightly etched; ordinary reflected light. Scale on illustration is 0.10 mm.

Showing minute oriented inclusions of spinel, judged to have formed as product of exsolution.

gabbro to the pyroxenite and to the richly magnetiferous pyroxenite that forms the ore; the evidence for magmatic conditions involving progressive changes in equilibrium and composition that were responsible for the conversion of an iron-poor pyroxene to a ferruginous hornblende; and the encroachment of the magnetite and ilmenite on both pyroxene and hornblende in the ore, all indicate that the magnetite is of late magmatic origin. It is essentially a "rest-magma," which, perhaps, plays the part of an "ore-pegmatite" to the basic differentiate, the pyroxenite.

Soda Alaskite-aplite Dikes (Specimen No. 4)

The white dikes previously mentioned as cutting the country rocks with which the orebody is associated are somewhat unusual because of their very low potash content and their high soda and silica percentages.

The potash in the samples collected is only 0.06 per cent; the soda is 7.17 per cent, and the silica 75.38 per cent (Table 2).

Analyses of rocks with less than one per cent potash and with high silica and soda have been previously reported;[32] but, despite the fact that such rocks are by no means uncommon, not many analyses have been recorded. The specimens represent diaschistic, quartz-feldspar

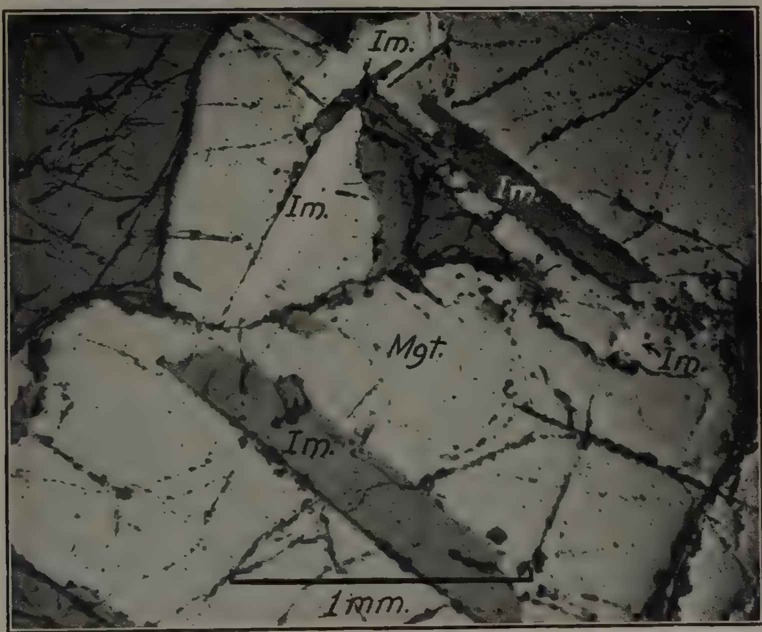

FIG. 12.—THE ORE, SPECIMEN 5. POLISHED SURFACE, POLARIZED LIGHT, NICOLS CROSSED.

Showing ilmenite (*Im*) in magnetite (*Mgt*). Greater part of ilmenite in several polished surfaces examined has this form and distribution. A little of it occurs in very small globules, similar to one marked *Im* in photomicrograph.

dike rock of the alaskite-aplite type. Quartz and alkali feldspar comprise 95 per cent of the rock, but the feldspar is unusual. Much of it is apparently untwinned, but between crossed nicols it exhibits an internal structure that gives a crude microscopic checkerboard pattern, although in ordinary light no traces of an intergrowth are visible.

The maximum refractive index of the feldspar is slightly higher than that of the balsam (1.537); the minimum index is distinctly lower. Occasionally patches in the larger crystals exhibit albite twinning, and some of the crystals show both albite and pericline twinning. The feldspar is judged to be a plagioclase of the composition $Ab_{90}An_{10}$; the

[32] U.S. Geol. Survey *Prof. Paper* 99 (1917) 76, 98, 104, 162, 244, 750, 936, 948, 950, 956, 958, 974.

"sodaclase" of Johannsen.[33] It is crowded with dust and vacuole inclusions and appears turbid in thin section, and it is slightly flecked with minute scales of sericite. Very small amounts of zoisite and epidote are distributed through the feldspar in the form of alteration aggregates, and in streaks and tiny veinlets, but the total quantity is insignificant.

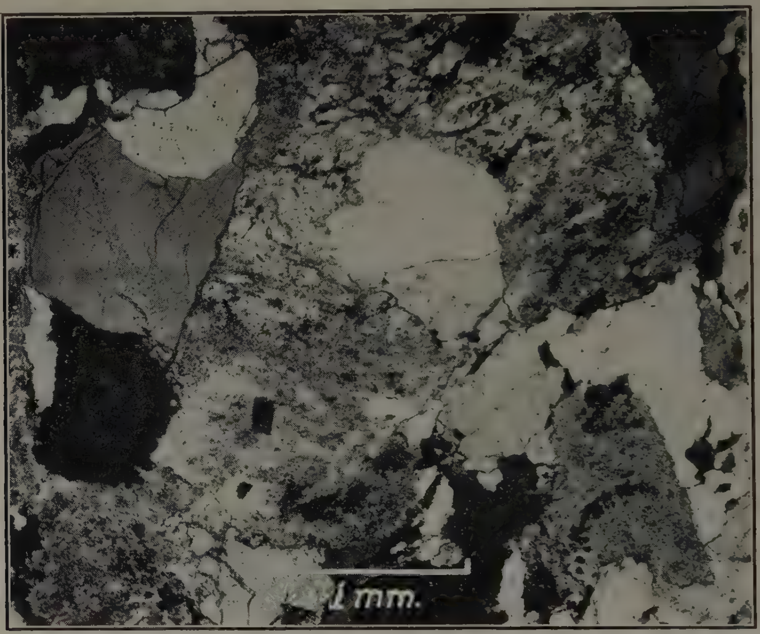

Fig. 13.—Specimen 4(c), alaskite-aplite; nicols crossed.

This specimen shows very little deformation. Turbid appearance of feldspar is due to innumerable inclusions, consisting of vacuoles, minute mineral grains and "dust." Many larger vacuoles are filled with liquid which commonly contains a bubble. "Dust" is probably composed of vacuoles so minute as to be almost beyond limits of vision. Quartz likewise contains numerous, and larger, vacuoles, filled with liquid and bubbles. One quartz grain, at upper right, shows slight strain polarization.

The quartz contains numerous liquid and bubble inclusions, and both the quartz and feldspar have granulated margins, some of the grains being thoroughly granulated and healed (Fig. 13).

One of the specimens evidently was taken from a strongly sheared dike, the rock being essentially a mylonite. Both feldspar and quartz are severely crushed and distributed in fragments along shear planes, and the small amounts of magnetite, epidote and zoisite present in the rock are similarly affected (Fig. 14). None of the specimens representing the gabbroic anorthosite, the gabbro, the pyroxenite or the ore exhibits intense shearing; and but one of the dike specimens shows such extreme deformation.

[33] A. Johannsen: Petrologic Abstract and Reviews. *Jnl. Geol.* (1926) **34,** 841.

There is no direct evidence connecting these dikes genetically with the series of Humacao differentiates; but their occurrence wholly within the series, and their extremely low potash and high soda and silica contents favors such a genetic connection rather than a conception of origin relating them to the granitic phase of the post-San Lorenzo intrusion.

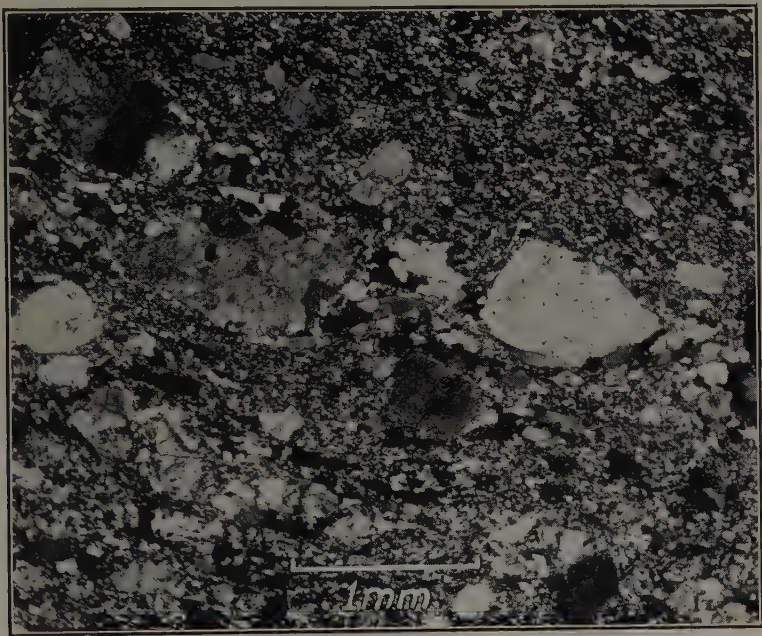

FIG. 14.—SPECIMEN 4(*b*), ALASKITE-APLITE; NICOLS CROSSED.
Showing intense shearing; a condition exhibited by only one of several specimens of these dike rocks collected. This particular specimen is essentially a mylonite; notwithstanding severe deformation which has affected it, rock is but slightly altered.

ECONOMIC POSSIBILITIES OF THE HUMACAO MAGNETITE

The exploratory work recently done on the Humacao magnetite is inadequate even for a rough estimate of the available tonnage. The tunnels made in 1899 are choked with debris, and only one remains open far enough for the ore to be observed in place. According to the incomplete records of the work done 35 years ago, the three tunnels at an elevation of 300 to 400 ft. penetrated ore at distances of 20 to 30 ft. from the surface, and one of them was extended 90 ft. through magnetite before work was stopped. A fourth tunnel, 80 ft. below the ridge crest, is reported to have gone through the hill from the north to the south side in ore, but the ridge is narrow at this elevation and the opening need not have been very long. Along the strike of deposit, ore has been traced for a distance of 2000 ft., but nothing is known regarding its width, depth or quality, except in the area prospected in 1899. Even for this

limited acreage the information can not be deemed sufficient for a reliable opinion.

Geographically and topographically the deposit is favorably situated for exploitation, and the abandoned workings show that intelligent use was made of these factors. The moderate to steep northern slope of the ridge invites the liberal use of gravity in handling the ore, and it is probable that the overburden is thin enough to permit open-cut mining, should development prove economically feasible. The ridge lies, moreover, at the edge of Humacao alluvial plain, which is threaded with a network of private and public roads; and cane railroads, radiating from Central Ejemplo, are near at hand. A spur not more than 2000 ft. long would connect the orebody with the main line of trackage, which runs from the sugar central to the port of Humacao, barely 6 miles to the east and north.

In itself, the Humacao magnetite deposit probably deserves little commercial consideration, but it seems to merit some study as a mining prospect because of the proximity of the nontitaniferous deposits in the contact zone that stretches from Las Piedras almost to Caguas. No one of the orebodies in this section of Puerto Rico is large enough to attract the investment necessary for large-scale mining operations; the aggregate of deposits, on the other hand, warrants thorough exploration, and the Humacao magnetite constitutes but one of the units to be considered among the problems of utilization. Although titanium is present in excess of the desirable minimum, it may prove feasible and economical to reduce the percentage by dilution with the nontitaniferous contact ores. Another possibility is suggested by the petrographic analysis of the ore: Much of the titania occurs in the form of ilmenite, which, because of its relatively coarse grain, manner of distribution, and moderate quantity, may be reduced, but not eliminated, by magnetic separation.

Further study of the prospect is desirable. A careful magnetic survey to determine the extent of the orebody, some judicious drilling to obtain estimate of tonnage, together with detailed petrographic analyses of selected samples and actual mill-run tests seem to be warranted from the results of the preliminary examination.

Application of Geology to Problems of Iron-ore Concentration

By T. M. Broderick,* Member A.I.M.E.

(New York Meeting, February, 1933)

Investigations into the possibilities of economically mining and concentrating low-grade iron ores of the Lake Superior region are attracting increasing attention. Among the organizations that are carrying on the work are the United States Bureau of Mines, the State of Minnesota (which spends about $80,000 annually on problems of the iron and ferroalloy ores of Minnesota), and the State of Michigan (which spends about $10,000 annually of its iron-ore research). Several of the mining companies are also financing research.

Of the states in the Lake Superior district, Minnesota has done most in iron-ore concentration. In 1930, thirty-seven concentrating plants were in operation on the Mesabi Range, beneficiating about one-third of the total ore shipped. About one-half of these plants reduced silica; the others reduced moisture or improved the structure of the ore.[1] Research into the possibilities of magnetic concentration of the Eastern Mesabi magnetite ores indicates that vast tonnages of that ore may be utilized at a profit in the not distant future. Magnetic concentration has also been tried at Sellwood, Ontario, on the Moose Mountain deposit, and at the Berkshire mine in Wisconsin on the magnetic ores of the Western Gogebic Range.

There have been few attempts to concentrate Michigan iron ores. In order to determine the possibilities of such concentration, iron-ore research has been carried on at the Michigan College of Mining and Technology for the past few years. After a general survey of the iron ores of the state, a program of more detailed experimentation was outlined, starting with work on the Ironwood formation of the Gogebic Range. The results of this research led to the belief that gravity methods will produce fairly satisfactory concentrates from the parts of the iron formation that are made up of comparatively thick alternating beds of rather high-grade ore and lean chert.

About 85 per cent of the iron and steel produced in the United States comes from ores of the Lake Superior district. The reserves of direct

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[1] E. W. Davis: Concentration of Mesabi Hematites. *Min. & Met.* (Nov., 1930) 518.

shipping ores are estimated as sufficient at the normal rate of depletion to last for a period of 20 to 30 years.

Fortunately, the belief is growing that there is a possible way of avoiding a total eclipse of the Lake Superior iron-mining industry when the high-grade ores are gone. Throughout the iron ranges there are quantities of rock 20 to 50 or more times as great in tonnage as the high-grade ores and containing from 20 to 35 per cent iron. Most of these are the rock types from which, by natural processes operating in locally favorable places, the greater part of the original silica content was removed when the high-grade ores were formed. While there are numerous varieties of these rocks, they are all alike in one respect; that is, they consist of an aggregate of minerals, one or more of which are iron-bearing while the others are not iron-bearing. They differ from one another chiefly in the species of minerals and in the grain size and relationships of these minerals to each other. These rocks are more or less fine-grained mixtures of iron-bearing minerals and gangue, and the question arises whether or not the known methods of ore dressing or some new method yet to be discovered can economically separate the ore minerals from the gangue minerals and deliver to the furnace a satisfactory product.

That the iron minerals can be separated from the gangue has already been proved beyond question, but can it be done economically, and, if so, how soon can that fact be demonstrated? Can a method of producing from low-grade iron formations a concentrate containing, say, 10 to 14 per cent silica be so developed that plants can be made to pay within the near future? Such concentrates, mixed with natural ores running 5 or 6 per cent silica, would conserve the natural high-grade ores. Could the technique be so improved that when the natural ores are exhausted the concentrates from the iron formations would be of such quality and cost that they could compete successfully with foreign ores at the furnaces? That is the problem confronting the individuals, industrial organizations, and political units whose interests lie in preserving the Lake Superior iron-mining industry. The problem is a difficult one and will require hard work, mutual understanding, and perhaps some sacrifice on the part of the fee owners, mining companies and political units.

For many years the Mines Experiment Station at the University of Minnesota has been working on the beneficiation and concentration problems of the Minnesota iron ores. E. W. Davis, who has reported their work, points out various difficulties which must be considered in treating the lean Mesabi ores; among them the complexity and variability of the structures and the moistures and analyses of the feed.[2] The mineral aggregates are exceedingly fine grained; furthermore, partial natural leaching in a large proportion of the lean ores has resulted in

[2] Reference of footnote 1.

leaving the silica hard and dense and mixed with soft porous iron oxide of about the same apparent weight. Therefore Mr. Davis concludes that "gravity concentrating processes are limited in their usefulness to ores of a definite structure, and there is little indication that developments along this line will materially reduce the burden on the high-grade ore mines." He also concludes that for a large proportion of the lean ores, "fine grinding undoubtedly will be required and a considerable amount of fine concentrate will be produced that must be sintered." As a means of separating the iron-bearing minerals from the gangue, he suggests magnetic roasting followed by crushing and magnetic concentration in stages; and, since this is costly treatment, he further suggests a method of keeping to a minimum the proportion of the feed so treated; namely, the removal of a considerable proportion of the ore as an acceptable jig concentrate, leaving only the jig middling or tailing to be subjected to the more costly fine-grinding, roasting, magnetic concentrating, sintering process.

Because of the great variety of types of iron formation in Michigan, it was hoped that the adaptation of geological classification to ore-dressing requirements might simplify the problem. The ideal situation would be to divide the iron formation into units of sufficient size to be of importance, each with its own characteristics significant in ore dressing. Thus certain blocks, horizons, or zones would be amenable to straight gravity methods, such as jigging and tabling. Others would be suitable for gravity concentration, while a middling product might be handled by some other method. Still others might not respond to any gravity method, but might be adapted to flotation, magnetic concentration, roasting followed by magnetic concentration, leaching, or direct reduction methods. How closely such classification of the low-grade materials can be made is yet to be determined. Enough has been done to suggest that "radical changes in structure and analyses of the ore," which are such a handicap in the use of gravity methods on most of the lean Mesabi material, can be largely avoided in some of the Michigan iron formation. The present indications are that there are large tonnages of iron formation that may be treated by jigging and tabling without much of the fine grinding and sintering which are so costly. On the other hand, of course, the basic cost of mining the Michigan iron formation will be higher than that of mining the Mesabi iron formation, just as is the case with the present high-grade ores, unless the Michigan ore can be mined by open-pit methods.

In summary, the problem is to find methods of so concentrating Michigan low-grade ores that, as soon as economically feasible, plants can be started which will contribute their concentrates to the ore shipped and thus conserve the high-grade ores. It is further hoped that the concentrating plants can then gradually take over an increasing pro-

portion of the burden and prolong indefinitely the iron-mining industry of the state. One of the first and most essential steps in the project is to classify the available iron formation into blocks of economic importance. Such a classification should be based upon the physical and chemical properties of significance in ore dressing.

Principal Types of Iron-bearing Formation

The predominant types of Lake Superior iron formation fall within three general classes: the so-called original iron formation, the original iron formation as altered by katamorphic agencies, and any of the

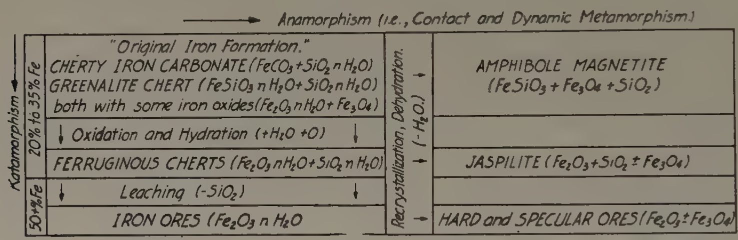


Fig. 1.—Geological classification of types of iron formation.

first or second class as altered by anamorphic agencies. The principal types of the three classes and their relationships to each other are shown in Fig. 1.[3]

Two types of rock constitute what is usually called "original iron formation." The cherty iron carbonate is a mixture of iron carbonate or siderite with chert. The greenalite chert is a mixture of hydrous iron silicate with chert. In both these types of original iron formation the iron is in the ferrous state. Usually included in the rocks called original iron formation, although strictly speaking they may be mildly altered phases of the two just described, are certain ferruginous cherts, consisting of more or less hydrated ferric oxide and chert, and the magnetite cherts of the main portion of the Mesabi Range, consisting of magnetite and chert.

The change from iron formation to iron ore takes place in two stages, the first of which oxidizes the ferrous iron to the ferric state. A completely oxidized iron formation consists essentially of hematite, with more or less limonite, and chert. It is called ferruginous chert, or, on the Mesabi Range, taconite. In most cases the change in iron content at this stage is probably unimportant. The second stage is the leaching of the silica, leaving the iron oxide as a residual product. This results

[3] The detailed discussion of the relationship of the various types of iron formation to each other will be found in the publications of the U. S. Geological Survey, especially in *Monograph* 52, by Van Hise and Leith, and in those of the state geologica surveys of Michigan, Wisconsin and Minnesota.

in increasing the iron content to 50 per cent or more. Since the changes from iron formation to ore are of the decomposing or destructive nature and result in mineral simplification, they are of the type called "katamorphic" by Van Hise. Most of the workers in Lake Superior iron geology regard the changes as having been effected by ordinary processes of weathering, although a few believe that the evidence points to hydrothermal waters of igneous origin as the agent.

In many places, the original iron formation or its oxidized and leached equivalents at any stage were affected by "anamorphic" processes, such as dynamic or contact metamorphism. The widespread occurrence of magnetite in the unoxidized phases of the iron formations seems to indicate that most of these formations have been subjected to a mild degree of anamorphism. Especially is this true of the Biwabik iron formation of the Mesabi Range, where by far the larger part of the iron in the unoxidized formation is in magnetite.

However, the anamorphic processes in many cases went much further and produced more profound changes than the early development of magnetite. Where the iron was still unoxidized, amphiboles, fayalite, and other iron-bearing silicates were also developed and formed the so-called "amphibole-magnetite" rocks. Where there was a deficiency of ferrous iron, the "jaspilites" were produced—hard, dense crystalline aggregates of specular hematite, quartz, and more or less magnetite. Because of their crystalline nonporous character, and because the fine-grained, more or less hydrous chert was changed into coarse quartz, these amphibole magnetite rocks and jaspilites are very resistant to the ore-forming processes, and therefore have not developed important orebodies. Except for the slight relative increase due to dehydration, their iron content now is practically what it was before anamorphism.

In some cases the processes of ore concentration were well advanced before anamorphism; if so, the product is also an iron ore, called "hard" or "specular" ore.

Significance of Geological Classification to Ore Dressing

The geological classification based upon the mineral composition and genetic relation of the various types of iron formation, as shown in Fig. 1, constitutes a logical foundation in the study of the concentration of the low-grade iron ores of the Lake Superior district. The chief properties that determine which of the various methods of ore dressing are applicable to a given ore are its mineral composition and texture. Therefore the usual geological classification shown in Fig. 1, being based in part upon mineral composition, can be used in a preliminary way to outline the various types of material available for concentration.

Inasmuch as the prime object of concentration is to separate the iron-ore minerals from the others, especially from the silicon minerals,

it is apparent that those types in which any considerable proportion of the iron is chemically combined with silica are undesirable. Ores of this type are the original iron formation with a large proportion of greenalite (such as some of the slaty members of the Biwabik formation of the Mesabi Range) and some of the amphibole-magnetite formations that have a high proportion of grunerite or other iron-bearing silicate. Since they are chemically combined, any physical methods of separation applied to such ores would have one of two undesirable results. Either the iron would go into tailings, or the silica would go into the concentrates. Thus, as material for concentration, those phases of the iron formation having iron-bearing silicates are undesirable in proportion to the amount of iron silicates present. Fortunately, the amount of iron formation eliminated for this reason is probably not large.

Solely from the standpoint of mineral composition, none of the other types of iron formation are objectionable.[4] The problem is the separation of the iron-bearing minerals from the silica. The specific gravity of the silica minerals varies from 2.66 for quartz to perhaps somewhat less for the more finely crystalline chert.

Some of the properties of the iron-ore minerals of interest in this connection are given in Table 1.

TABLE 1.—*Properties of Iron-ore Minerals*

Name	Composition	Fe, Per Cent	Specific Gravity
Siderite	$FeCO_3$	48.2	3.85 ±
Hematite	Fe_2O_3	70.0	5.0 ±
Goethite	$Fe_2O_3H_2O$	62.9	4.3
Limonite	$2Fe_2O_33H_2O$ (approx.)	59.8 ±	3.8 ±
Magnetite	Fe_3O_4	72.4	5.175 ±

In the great majority of cases the problem is one of separating the silica gangue of specific gravity 2.65 from some combination of the iron-bearing minerals having specific gravities varying from 3.8 to over 5. If the texture is favorable, gravity methods should do this without difficulty. The strong magnetism of magnetite offers a means of separating that mineral from its nonmagnetic associates, the chief difficulty in the case of the Lake Superior magnetites being that its intergrowth with the gangue is in many cases very fine grained. Furthermore, the other iron minerals, by means of a reducing roast, can be rendered magnetic and thus be made susceptible to magnetic concentrating

[4] Special phases present special problems because of their phosphorus, titanium, manganese or sulfur content. These are not considered in this discussion, although they are recognized as presenting important problems.

methods. Therefore, so far as mineral composition is concerned, the iron formations of the Lake Superior region are favorable to concentration.

Textures of Iron-bearing Formations as Related to Ore Dressing

The chief problems in concentrating the iron ores arise from the unfavorable textural features which many of them possess. The outstanding problem for the geologist at the present stage of the investigation is to classify the iron formations further on the basis of textures. A start in this direction has already been made, especially by the detailed stratigraphic work which has resulted in many subdivisions of the iron formations of the Gogebic and Mesabi ranges. Having made both a mineral and a textural classification of the iron formations, the geologist can supply the testing laboratory with the most favorable material occurring in important amounts.

Since the iron formations are all sedimentary rocks, they show bedding structures, conveniently called banding, which have persisted throughout the various katamorphic and anamorphic changes experienced by the iron formations. The thickness, the contrasts in mineral composition, and the iron content of these bands determine the behavior of the iron formation types under various methods of ore dressing. A rough classification according to the first of these features divides the bands into thick and thin (Fig. 2). Though varying with the ore-dressing method used, the classification generally includes among thin-bedded ores those whose bands are less than ⅛ in. thick. According to their iron content bands may be classified as rich, containing more than 50 per cent iron; medium, containing from 25 to 50 per cent; and lean, containing less than 25 per cent. Different bodies of iron formation then can be assigned to the following classes, based mainly upon thickness and iron content of the bands, a third classification being added to include some of the more massive ores in which banding is subordinate and the iron-bearing minerals are disseminated throughout.

- A. Banded
  - I. Thick banded
    - a. Alternating bands of rich and lean
    - b. Alternating bands of rich and medium
    - c. Alternating bands of medium and lean
    - d. Bands of rich, medium, and lean
  - II. Thin banded
    - a. Alternating bands of rich and lean
    - b. Alternating bands of rich and medium
    - c. Alternating bands of medium and lean
    - d. Bands of rich, medium, and lean
- B. Disseminated
  - I. Coarse
  - II. Fine

During the past few years the ore-dressing laboratory at the Michigan College of Mining and Technology has tested numerous iron ores from the various Michigan ranges. These ores have been studied macroscopically, and microscopically by means of polished sections, and on the basis of such study have been assigned a place in the classification above. In general, the results of the tests are what would be expected from this classification.

One of the first tests to be made was the float and sink test. First a screen analysis of the ore was made. Then the different sizes were

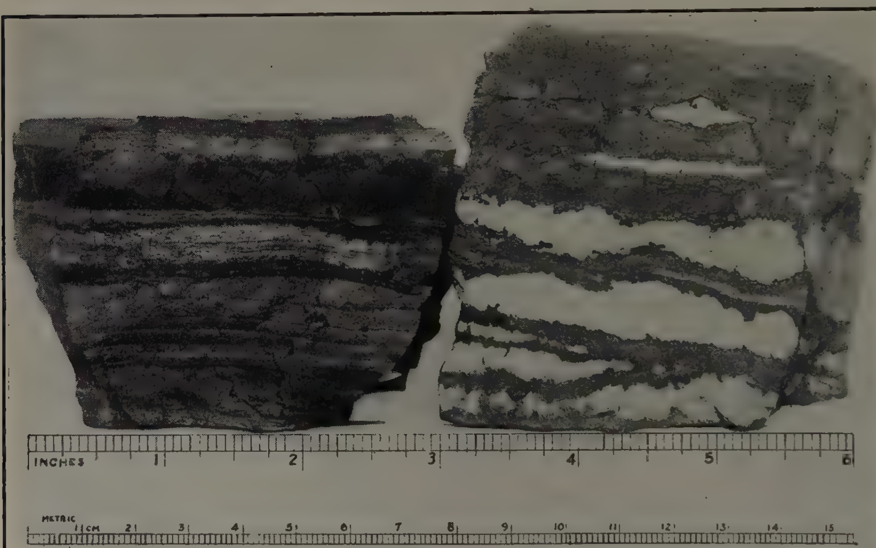
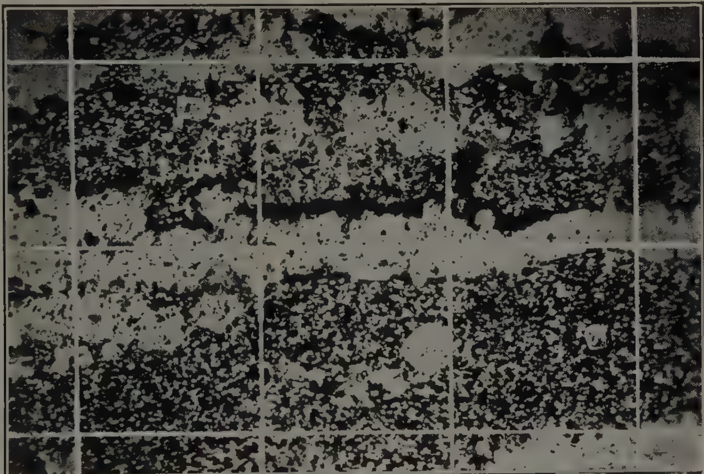


FIG. 2.—THIN-BEDDED (LEFT) AND THICK-BEDDED (RIGHT) IRON FORMATION IN HAND SPECIMENS.

separated into a heavier and a lighter portion by being placed in heavy solution. Acetylene tetrabromide solution of specific gravity 2.94 was selected as giving a fairly reliable indication of what the behavior of the ores would be when they are treated by gravity methods of concentration. A correlation of results obtained from macroscopic and microscopic examination with those obtained from float and sink tests and from jig and table tests enables the investigator to feel confident in using the first method to predict the amenability of an ore to treatment by gravity methods. Examples of this correlation of texture with the results of testing follow.

Ore No. 109, from the upper part of the Plymouth member, Ironwood formation of the Gogebic Range, is shown in hand specimen on the left side, Fig. 2. Its thin bedding is apparent. The sample runs 35.12 per cent iron. The float and sink tests show that the sinks assay 42.52 per cent and the floats 17.31 per cent. Even in the finer sizes the same

characteristics of low-grade sinks and high iron in the floats persist. Fig. 3 is a photomicrograph of a characteristic polished section of this ore. Very thin beds of the richer material are 0.046 mm. thick, the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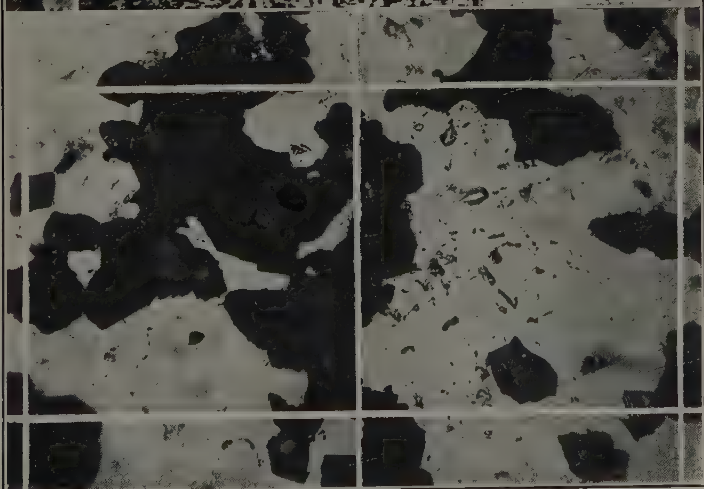
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Fig. 3.—Ore 109. Thin-bedded ore from upper part of Plymouth member, Ironwood formation, Gogebic Range.

Banded and disseminated hematite (light) in chert matrix (dark). Grid is 0.140 mm., the size of opening of 100-mesh screen.

Fig. 4.—Ore 90. Thick-bedded ore, Negaunee iron formation, Marquette Range.

Shows complex intergrowth of limonite (light) and chert (dark) which constitutes the richer bands in the ore. Grid is 0.074 mm., the size of opening of 200-mesh screen.

diameter of the opening in a 300-mesh screen. Between these richer beds are leaner bands in which the hematite occurs in disseminated particles of 0.0045 mm. dia. The reason for the low-grade concentrate

and the high iron content of the tailings is evident. The richer beds can be separated from the others only by very fine grinding, and even then the chert of the poorer beds carries considerable iron as very finely disseminated hematite. Gravity methods would be hopeless with such an ore. It would be classified as thin-bedded with alternating rich, medium rich, and lean bands.

Ore 90 is a fairly thick-banded ore from the Negaunee iron formation. The separation of the richer from the poorer beds by gravity methods after relatively coarse crushing was not difficult. However, the float and sink tests were discouraging. The ore runs 32.90 per cent iron, the sinks 42.38 per cent, and the floats 12.96 per cent. The grade of the sinks in the finer sizes is no better than in the coarser sizes. While the low iron content of the floats indicates that an acceptable tailing could be made, the low iron content of the sinks indicates a poor concentration. The low grade of the sinks is explained by the fact that the richer bands, as shown in Fig. 4, consist of a complex fine-grained intergrowth of limonite and chert. A physical separation of the limonite and chert would require a prohibitive degree of fine grinding. This ore falls in the classification above as coarse-banded, with alternating bands of medium and lean grade.

Ore 100 is a jaspilite from the Marquette Range. Because of its abundance and prominence in outcrops, and perhaps because of its rather spectacular appearance, it naturally attracts attention as a possible concentrating ore. Mineralogically it consists of hematite, both bladed (or specular) and martitic, much of the martite showing residual or unreplaced magnetite. The hematite is all more or less disseminated in a chert gangue. The bedding, although very pronounced, does not serve as a basis of separating the iron values. There are two reasons for this: many of the beds are very thin; and the richer contain considerable chert, while the poorer contain considerable iron. The float and sink tests were very unsatisfactory. The sample contains 34 per cent iron, the sinks about 37 per cent and the floats about 18 per cent. The separation in the finer sizes was not much better than in the coarser sizes. Polished sections under the microscope clearly reveal the reasons for the low-grade concentrate and the high iron in the tailings. Fig. 5 shows the essential features that are significant in explaining this behavior. One of the wider bands, about 0.220 mm. thick, or about the diameter of a 60-mesh particle, is shown running through the center of the field. It consists of an aggregate of magnetite crystals, largely oxidized to martite, the interstices being filled with chert. It is flanked on both sides by chert which contains very fine disseminated hematite and also very thin beds consisting of fine-grained hematite and chert. Obviously the results to be expected from grinding to 100 mesh would be particles of which the richest would contain considerable chert and the others

considerable hematite. This is consistent with the results of the float and sink tests and demonstrates that gravity methods would be unsatisfactory for this ore. It would be classified as thin-banded, the alternate bands being of medium and poor iron content.

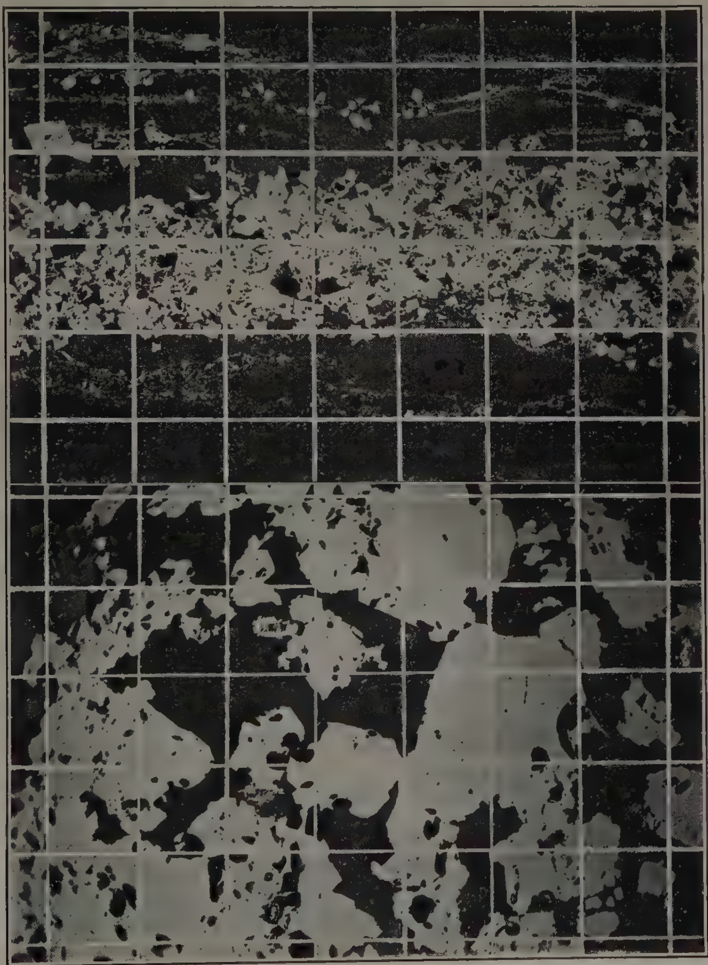

FIG. 5.—ORE 100. JASPILITE, NEGAUNEE IRON FORMATION, MARQUETTE RANGE. Martite (light) with some residual magnetite, in chert matrix (dark). Grid is 0.140 mm., the size of opening of 100-mesh screen.

FIG. 6.—ORE 50. AMPHIBOLE MAGNETITE ORE, MARQUETTE RANGE. Magnetite (light) in quartz-amphibole gangue (dark). Grid is 0.140 mm., the size of opening of 100-mesh screen.

Ore 50 is a massive quartz-magnetite aggregate from the Marquette Range. Bedding is present, but the outstanding feature of the magnetite distribution is its interlocking relationship with the quartz. The iron content is 48.60 per cent. In a float and sink test, the sinks ran 49.94

per cent and the floats 8.82 per cent iron. The separation was much better on the −65-mesh sizes than on the coarser material. Fig. 6 shows the rather coarse interlocking and disseminated texture of the magnetite. Because of the grain size, such fine grinding would be required to set free the magnetite that the feed would be too fine for gravity methods; however, it seems probable that some magnetic method of concentration might succeed. Of course, fine grinding of the feed means sintering of the concentrate, a handicap that ores amenable to gravity methods of concentration do not have. Ore 50 would be classified as moderately coarse disseminated.

The foregoing are examples of some of the types of iron formation that, by examination both macroscopically and microscopically and by the float and sink tests, are shown to be unsuited to gravity methods of concentration. While they offer no difficulties because of their mineralogical character, they are too fine grained to allow separation of the iron minerals from the gangue except by fine grinding. The most likely methods of treatment so far suggested for such ores are flotation or reducing roasting (unless the iron-bearing mineral is magnetite to start with) followed by magnetic concentration. Sintering the concentrates would be necessary. Another type of ore unfavorable to gravity methods is that in which, because of partial leaching, the iron-rich particles are porous and the chert is nonporous. In such cases the weight of the iron particles may approach that of the chert particles of the same size and thus make gravity separation difficult or impossible.

Perhaps the larger part of the iron formations of the Lake Superior district, including Michigan, is of the type that will require fine grinding and sintering. The published discussions of the concentration problems of the Minnesota iron ores (other than the wash ores) indicate that such is the case in Minnesota.

In Michigan, the Ironwood formation of the Gogebic Range has been the object of detailed stratigraphic study for some years. W. O. Hotchkiss[5] subdivided the iron formation into various horizons based upon their stratigraphic character. Recent work indicates that, with some modifications, these stratigraphic subdivisions serve to separate the formation into horizons which are of varying amenability to concentrating processes. Of particular interest is the fact that Hotchkiss's wavy-bedded members are characterized by alternating fairly thick beds of high-grade ferric oxide and chert. There are three of these wavy-bedded horizons, called the Plymouth, Norrie and Anvil members, which together make up, on the average, over one-half of the iron formation. Between these horizons the iron formation is made up of thinner, even-bedded material. It is apparent that these two types of formation,

[5] W. O. Hotchkiss: Geology of the Gogebic Range and Its Relation to Recent Mining Developments. *Eng. & Min. Jnl.* (Sept. 13, 20, 27 and Oct. 4, 1919).

the wavy, thicker bedded and the even, thinner bedded (Fig. 2), differ in their adaptability to gravity methods. The thin-bedded material is of the nature of No. 109 or No. 100, as described above, and requires fine grinding, perhaps reducing roasting, followed by magnetic concentration and sintering. In the tests so far made the wavy thick-bedded horizons, on the other hand, have shown themselves to be adapted to concentration by gravity methods. The concentrates so made are not far from being an acceptable furnace product in size and analyses.

A characteristic ore is No. 149, which is from the lower 130 ft. of the Plymouth member of the Ironwood formation. It is all wavy thick-bedded material, the bands of which consist of both hematite and limonite with some manganese oxide and intergrown chert alternating with lean cherty bands. The material runs a little over 30 per cent iron. Float and sink tests showed that it has good possibilities, a fair separation of the iron being obtained.

Jig tests in which a heavy medium[6] was used were run on 90 per cent of the sample, consisting of the portion from −2-in. to +10-mesh material. Sixty-four per cent of the iron in these sizes was recovered in a concentrate running 59 per cent iron plus manganese and about 10 per cent silica. Eight per cent of the iron was contained in a middling assaying 22 per cent iron. The tails assayed 9 per cent iron.

The nature of this ore is well seen in polished section. Fig. 7 shows the massive aggregate of iron oxide in the richer bands. Such material is very rich and cannot be improved by any practical method of separation. Microscopic examination of the middlings indicates that some of it can be concentrated by gravity methods after finer grinding. Some of the middlings, however, such as shown in Fig. 8, consist of such a fine-grained intergrowth of iron oxide and chert that gravity methods cannot handle the products of the fine grinding necessary to separate the values.

Similar encouraging results on the Plymouth member have been obtained on other samples. Thus there appears to be real foundation for the hope that about one-half of the Ironwood formation of the Gogebic Range in Michigan, consisting of the three wavy-bedded members, can by gravity methods be made to yield an acceptable concentrate, a final tailing and a middling product. The middling product may require the more expensive methods of treatment to recover its iron.

The tonnage of the wavy-bedded members on the Gogebic Range in Michigan is enormous. Assuming the length to be about 12 miles and the width 400 ft., there would be about 250 million tons for every 100 ft. in depth. The mining of such material would present special problems of considerable difficulty. The brevity of the present discussion does

[6] F. J. Tolonen: Gravity Concentration Tests on Michigan Iron Formations (in preparation).

not indicate that these problems are overlooked or minimized. As the dip of the formation is about 60°, it would not be possible to mine, say, a 150-ft. width of the Plymouth member by open pit or by quarrying to any great depth. If only the wavy-bedded members were to be mined,

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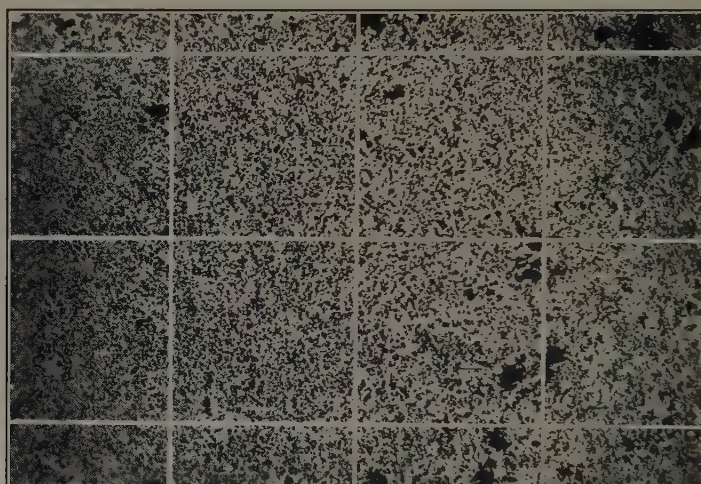

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Fig. 7.—Ore 149. Plymouth member, Ironwood formation, Gogebic Range. Shows microstructure of dense very high-grade beds, constituting much of jig concentrates. Massive aggregate of hematite (light) with a few areas of chert (dark). Grid is 0.140 mm., the size of opening of 100-mesh screen.

Fig. 8.—Ore 149. Plymouth member, Ironwood formation, Gogebic Range. Fine-grained middling product consisting of interlocked goethite (light) and chert (dark). Grid is 0.074 mm., the size of opening of 200-mesh screen.

it would be necessary to employ underground methods, just as are now used for the high-grade ore. If, however, these horizons are as uniform in their characteristics as present knowledge indicates, they

could be mined continuously from one end of the district to the other, so that the mining costs per ton of iron formation would run lower than costs per ton of iron ore. The costs of exploration would be largely eliminated, for the accumulation of data in the exploration for the high-grade ore could serve to outline the horizons of the iron formation. Perhaps the present developments with their shafts and other available underground openings would make it economically possible to mine and concentrate such iron formation in the not distant future. If, however, the problem of economically treating the two thin-bedded members of the iron formation should be solved, then open pits on the 600 to 800-ft. width of the entire iron formation could be carried to considerable depth. Under such conditions the rock from the wavy-bedded members could be sent to the jigs and that from the thin-bedded members to the other parts of the plant.

Procedure in the Laboratory and Field

To be of service in this study the geologist should become familiar with the fundamental features of the processes of ore dressing. On his appreciation of these basic principles depends his ability to grasp the significant points that will guide him in his sampling. If he follows certain ores through the tests, he can draw off specimens at various stages for examination. By microscopic examination of polished surfaces he can readily see why the concentrates are low-grade or why there are losses in the tailings. He can frequently determine whether or not a middling product can be successfully retreated.

By making repeated comparisons of the polished sections, and of the results of float and sink tests and of larger scale laboratory tests, the geologist gradually acquires some skill in predicting how an ore will respond to treatment.

In the field his chief function is to reclassify the iron formation into units, such as horizons, zones, or areas, each with its own peculiarities significant to ore-dressing behavior. The principal bases of these subdivisions—mineral composition and texture—have already been noted. Size of the units, of course, is of importance, since the study has an economic purpose. Having classified the iron formation into unit masses of uniform characteristics from the ore-dressing standpoint, the geologist should next take samples to be used in testing the behavior of this particular kind of iron formation in the laboratory.

The samples used in the ore-dressing tests vary in size. One hundred pounds or less is sufficient material on which to perform preliminary tests for determining general characteristics. It has been found that these smaller samples are likely to have a somewhat lower iron content than larger samples of the same material. For more extensive tests, samples of from ½ ton to 25 tons have been taken.

Summary

There are many different types of iron formation in Michigan, each with its own set of physical properties and with its own geological distribution. Thus the matter of selecting units to be studied for their concentrating possibilities is related to a modified system of geological classification. The results of tests of Gogebic Range iron formation illustrate the desirability of making such classifications of the iron formation the bases of sampling, inasmuch as the different types of the iron formation on that range respond quite differently to ore-dressing methods. The wavy, thick-bedded portions offer encouraging possibilities of adaptation to gravity methods of treatment of the fairly coarse sizes.

Acknowledgments

This study is being carried out as a part of the iron-ore research program of the Michigan College of Mining and Technology. The writer is indebted to Dr. W. O. Hotchkiss for information concerning the stratigraphy of the iron formation of the Gogebic Range. The hearty cooperation of all of the mining companies on that range is acknowledged. The members of the different staffs have been particularly generous in giving their time and information in the course of the field studies.

DISCUSSION

D. E. Woodbridge, Duluth, Minn. (written discussion).—Mr. Broderick's paper is important. However large the iron-ore supplies in other parts of America may be, the economic situation has resulted in drawing on those of Lake Superior for about 85 per cent of average demands. So far as we can see, this situation will continue, modified to some extent by the growth of industrialism and of congestion of population in the South and West.

While the day of exhaustion of natural commercial iron ores is far off, the date of peak production is not distant. In fact, perhaps we have passed it; it is not unlikely that 1916, with the shipment of 66,903,400 tons from the Lake region, was that year. The down curve will be long and very gradual, but the decline will be compensated more and more, as years pass, by the products of beneficiation. And by the word "beneficiation" I refer not so much to those methods now in vogue, such as crushing, washing, jigging, drying and sintering, etc., of hematites, which now represent about one-third of total Lake Superior production, as to those more complex methods that have to do with magnetic ores.

This being the case, anything that will simplify the problem of the magnetites is of great present interest and of more importance for the future.

Mr. Broderick says that "there have been few attempts to concentrate Michigan ores." But in the two decades prior to 1900 there were many efforts at concentration in Michigan. These were of more importance when looked at in the light of statistics of that time than if viewed with production figures of the present in mind. That work was on various classes of iron ore. In the Transactions of the Institute during that period much space was devoted to discussion of the subject. There was a works at Negaunee to enrich specular hematite by crushing and jigging. At Republic and

other Marquette County mines there were plants of generally similar type, and there were magnetic separating plants on the Menominee Range. Ball-Norton, Wenstrom, Buchanan, Chase and other types of machines were used. I presume that most of these efforts were based on work that had been done in New York, New Jersey and North Carolina.

From the beginning of these and other attempts at concentration it has been recognized that where magnetic separation was possible it was the desirable method, but I doubt whether there ever has been due recognition of the varying degree of magnetism in naturally magnetic ores.

Reference is made to the possibility of subjecting hematite ores to magnetic separation, after a preliminary magnetizing process. It seems to me that the discussion of a process which requires crushing, separating, magnetic roasting, fine grinding, magnetic separation and sintering to secure a material that is worth in a distant market only about ¼¢ per pound must be considered as quite academic.

The tonnage of these naturally magnetic ores around Lake Superior—on both sides of the international boundary—is so vast that a scientific effort to so classify them as to simplify the problem of separating iron from gangue is of a value scarcely to be realized—and that is just what the Michigan College of Mines is attempting and Mr. Broderick is explaining.

Relation of the Mining Geologist to the Mining Industry in the Birmingham District, Alabama

By C. S. Blair,* Member A.I.M.E.

(New York Meeting, February, 1933)

The development of a geological department as an integral part of the Tennessee Coal, Iron & Railroad Co. in the Birmingham district, Alabama, in 1908 was an innovation probably unique for any mining organization south of the Ohio River. At that time a few of the oil companies were starting geological departments, but there were no geologists among the larger industrial organizations. The Tennessee Coal, Iron & Railroad Co. had been a substantial producer of pig iron for many years and was just getting a start in the manufacture of steel products from the pig iron. It had large acreages of coal land, ore land and timber land, but there was lacking the detailed knowledge of the possible mineral resources of much of its territory, and this territory at that time covered an area in the neighborhood of 500,000 acres in the states of Alabama, Tennessee and Georgia.

Those responsible for the operations of the mining properties, not being familiar with the kind of help that might be expected from geologic work, were decidedly skeptical of the utility of the work. Therefore it was necessary to develop cooperation with the mining organization, by not infringing upon its functions, and by developing the work in such a manner as to demonstrate to the mining department its practical utility.

In the first instance the man responsible for a mining operation is apt to assume the attitude that the geologist is a blockader, because the geologist, unfortunately, is obliged to point out difficulties in the carrying out of mining operations in the way originally planned. He points out the dangers of mining out one coal or metal seam at the ultimate expense of an upper or lower seam, and he develops structural features, such as faults and folds, which call to the attention of the mining operator difficulties in his future operations, which the latter had not anticipated.

Eventually, however, the value of having these data became apparent to the Tennessee Coal, Iron and Railroad Co., and the operators not only welcomed the geological work and cooperated fully in its acquisition of essential information, but reached the point of asking assistance and advice; and complete coordination of the two activities has existed for many years.

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A broad distinction that may be drawn between the work of the mining geologist in the Birmingham district and the work of a geologist in connection with metalliferous deposits and lode mining, of which the features have been more generally and widely treated in literature, is that in connection with most of the precious and base-metal deposits, the work of the mining geologist is confined to very limited areas, which might be treated in terms of acres, while in the Birmingham district the important deposits are bedded in nature within relatively flat-lying sedimentary formations, and are treated in units of square miles. While the structural details are much simpler than in areas of extreme structural deformation characteristic of most metalliferous mining, the very simplicity of this detail renders the ascertaining of facts useful to mining operations extremely difficult of determination, and through years of practical experience a special technique has been developed to meet this situation.

Economic Work in Birmingham District Restricted to Company Geologists

Commercial geologists in the Birmingham district are practically limited to those employed by mining corporations. The amount of geologic work available outside of the major companies is very small, and probably will always be so. The predominant position of the company geologist is due to his more detailed knowledge of the district gained from the large amount of confidential geological and mining data available to him. One of the major requirements for the success of a geologist with a corporation is the early assimilation of all data already available bearing on its mineral reserves. A thorough prospecting campaign is also usually carried out during the beginning of his work to supplement these data and establish at least in a general way the important mineral values on the entire acreage. The possession and proper interpretation of these prospecting and mining data give him a knowledge of the entire district and place him in a position to assist mining operations which cannot be approached by an independent geologist irrespective of his preliminary training.

Functions of the Mining Geologist

The function of the mining geologist is the careful study of the mineral deposits of his particular district, so as to determine, in so far as is possible in advance of mining, such features as the quality, thickness, recoverable tonnages, etc., and the structural relations, such as dip, strike, faults, folds, etc., that will affect future operations. It will be recognized that the prediction of the structure of an undeveloped mineral body in this Southern Appalachian field often goes beyond geological possibilities, and involves imaginative powers of which the geologist is often accused of having too large a supply. His assistance to the mining industry,

however, is governed largely by the accuracy of his preliminary estimates of the character and structure of an undeveloped mineral deposit.

It should be emphasized that fundamentally the geologist's work is in advance of and not directly connected with mining operations. It is limited to undeveloped mineral deposits even where all the field evidence is secured from mining operations, as in the prediction of the position of an ore or coal bed beyond a fault encountered in the mine. To the geologist, present mine workings afford an important interest in that they supply data on which to base certain conclusions as to the probable mining conditions in other areas, in advance of future operations. His province should be limited to the prediction of the character and structure of the deposit. The method of mining ore of a certain grade and occurring in certain structural conditions, or what ore, if any, should be mined, are matters outside his field even though he may have definite opinions as to the fitness of the mining methods to meet the conditions. The old adage, "Let the shoemaker stick to his last," should apply to the geologist on mining methods. The same restrictions apply to the mining engineer concerning geological problems, especially in connection with estimates of ore tonnage. Mining engineers have made outstanding mistakes in determining whether an adequate ore supply exists before locating a plant in a new district. Examples near home are the Alabama graphite district, where during the war period over 50 plants were constructed of which only three or four had any commercial production; and the Batesville, Arkansas, manganese field where 15 concentrating plants were built, none of which had any commercial possibilities even with war prices. Practically all these plants were well designed and constructed with average costs above $100,000 each, but the ore supply was pitifully inadequate.

As in other lines of work, the personal element is an important factor with the company geologist. He must establish close contacts with the mining department, if he is not directly connected therewith, and be in a position where he can have access to all mining data in the company's operations, and be advised of all unusual mining developments. In the manufacturing field, where his contact is ordinarily not as close, it is even more important that the most friendly personal relationship be established in order that he may know its problems in such materials as refractories, fluxes and special products on which he may be in a position to assist. Such relations are also important in dealing with outside mining companies and the mining profession of the district, and affect greatly the amount of information the geologist is able to secure from them. Our experience has proved that the mining geologist must be familiar with the mining developments on adjacent properties, and be in a position to make surface examinations or visit their mining operations when desired. He cannot successfully confine his prospecting work or

geological studies to his company holdings. Often, in working out structural problems, information from a neighboring mine is just as valuable as that from his own company's operations, and with good personal relationships, and with an understanding that all information secured from outside operations is on a give and take basis, the mining developments of the district are wide open to him, so that he is consulted on unusual mining developments and special structural problems much as a doctor is for a sick patient.

The mining geologist must pay his way. He must remember that his work is on a commercial basis and must be limited to fields that promise financial return to his company. The cost of his department must be more than offset by the savings he effects either in connection with mining operations or with other departments of his company. This point is important also in connection with the undertaking of studies of special research problems, and unless a problem has promise of commercial return to his company within a reasonable period, special research studies must be left to the independent investigator or the state or federal bureaus.

Geological Department of Tennessee Coal, Iron & Railroad Co.

The initial duties of the geological department of the Tennessee Coal, Iron & Railroad Co. embodied taking stock of its mineral resources through detailed study, classification and proper recording of all available data concerning reserves, including diamond-drilling, surface prospecting and miscellaneous mining data. An important phase of this preliminary geological work was the proper classification of the data in permanent filing of records, which could be successfully enlarged as necessity required. The preparation in desirable form and proper filing for easy reference of all accumulated geological data was a rather imposing task, involving long continued detailed drafting work under geological direction, including the platting of drill records with analyses, mine sections, geological cross-sections, and preparation of general maps, etc. The geologist usually will find much patient checking of these data required, especially of drill records, before coal or ore seams can be definitely correlated. The particular form used for filing records is not considered especially important provided it is elastic and can take care of necessary future enlargement, but the system adopted must be followed consistently.

Too much emphasis can hardly be placed upon the necessity of the immediate establishment and maintenance of a proper filing system for recording all geologic information accumulating not only from his own company but from outside sources. A successful geological department must always be in a position to furnish information promptly when called on, and must have quickly available for reference a great mass of detailed mining, drilling and general prospecting data on the entire district, which may be seldom used but any part of which may be essential

in working out some geological problem. The completeness, permanence and confidential character of this geological file materially affects the general usefulness and standing of the geologist not only with his own company but also with outside companies. In more than one instance outside mining companies have been able to secure diamond-drill records

FIG. 1A.—SKETCH MAP OF BIRMINGHAM DISTRICT.

and other data that they had given to us but which had been lost from their own files.

Combined with the study and proper correlation of all existing data was a general prospecting campaign to cover in a preliminary way the entire company holdings, to afford the geologist sufficient data to prepare

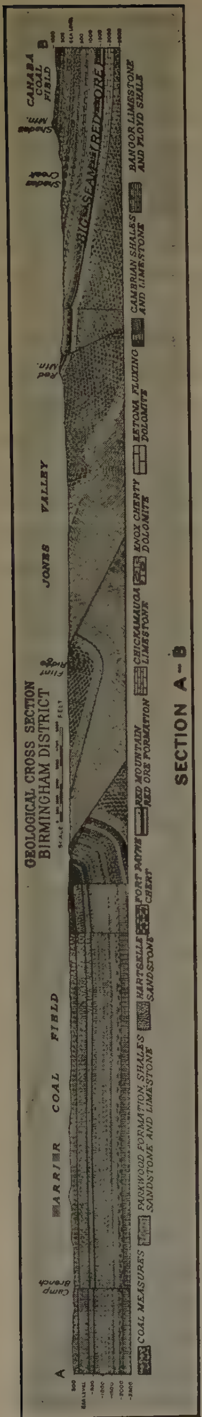

FIG. 1B.

preliminary estimates of the company's mineral resources. A prospecting campaign based on diamond-drilling and surface prospecting requires substantial expenditures, so that the approval and support of the management and mining department is a prime necessity.

The relationship of geological work to the mining industry in the Birmingham district may be discussed to best advantage by describing the actual work of this department in connection with our principal raw materials, especially coal and iron ores, from the preliminary prospecting of the mineral lands to the assistance to present and future mining operations. The conditions that confronted the geologist at the beginning of work in the Birmingham district are not typical of what he would ordinarily encounter today, because such extensive acreages of unproved land under one ownership are unusual.

Prospecting of Mineral Reserves

In the Birmingham district the prospecting work has been of various types corresponding to the field covered. In Fig. 1, a sketch map of the Birmingham district, are outlined the chief coal fields, the Warrior and Cahaba, the Clinton red ore territory, and the limestone or dolomite belts underlying the valleys between. They furnish the principal raw materials. The structural relationship of these areas is shown by the geologic cross-section *AB* extending from the Warrior field through the Clinton red ore area into the Cahaba coal field.

The prospecting of the coal lands which are included in the Warrior and Cahaba fields in the Birmingham district and the Cumberland plateau field in Tennessee was started almost with the beginning of this department, and has continued with intermissions up to the present.

The Warrior Coal Field

The predominately important Warrior field adjoining Birmingham on the west is underlain in general by low dipping measures, and contains

the coking-coal reserves of the district. The surface prospecting of the principal coal seams in the coking-coal area in the eastern part of the Warrior field, which includes approximately that part east of the 65° isocarb, has been relatively unimportant because these seams outcrop only in the steeply dipping, faulted measures on the margin of the field, where upturned against the boundary fault. In this coking-coal area diamond-drilling has been depended upon to prove up the thickness and quality of the coal seams, the principal seams being limited to two important groups, including the Pratt and American group above and the Mary Lee or so-called Big Seam group approximately 500 to 600 ft. below.

These Warrior field coking coals are of a friable, soft physical character and contain numerous partings, so that in diamond-drilling the recovery of the complete core is essential for the proper record and analysis of the seam. The diamond-drilling has been done under the close supervision of a geologist who logs the core, checks it closely with all adjacent holes for unusual features, and advises the driller as to the expected depth of the important coal seams. Our experience has proved the value, even in areas of apparently uniform conditions, of preparing detailed logs of all drilling, checking closely all changes in sedimentation, recording carefully the dips of the strata and paying especial attention to unusually high dips or indications of faults.

The diamond-drilling in the Warrior field has been of two general types, including the close drilling connected with mining operations and the more general drilling of undeveloped acreage. In special areas for new mine operations, or adjacent to present mining operations, the holes are closely spaced and located with reference to plans of the mining department. In this class of drilling is included a large amount of underground drilling in the mines for lower seams, such as drilling to the American or Mary Lee coal below the present Pratt mine workings.

The second and principal type of coal drilling has been to test the coal on undeveloped areas or on lands held under option for purchase. The location and number of these drillholes are decided by the geologist. The locations are determined by the results of the current drilling and follow indications of original basin structures or trends of thicker coal. In such areas it is usually necessary to combine surface prospecting and geological mapping with the drilling in order to work out the structural conditions affecting future mining operations. This combined drilling and structural work should give data sufficient for detailed estimates of the recoverable tonnage, average analyses of the coal both in the raw and washed state, and a reasonably accurate contour map of the coal surface. Mining operations can then be planned with confidence as to conditions that will be encountered, with the possible exception of roof conditions. Experience has shown that roof conditions in mining operations are dependent on so many factors—including especially

structural conditions and the character and thickness of the overlying strata—that they can be determined definitely only by actual mining practice.

In the northern part of the Warrior field, where the Black Creek and Mary Lee groups of seams outcrop, the principal data on the coals have been derived from surface prospecting. The coal outcrops are generally deeply weathered and difficult to trace and can be followed only by cutting the coal occasionally. At selected favorable places—usually 1000 to 1500 ft. apart—small open cuts or adits are extended under cover, usually from 20 to 30 ft. from the outcrop to a point where the coal shows normal thickness and physical character, so that it can be sampled. A detailed record is kept of each cutting, showing the coal section, character of top and bottom, strike and dip of strata, distance driven, etc.

In many places surface prospecting gives much more dependable data on the average thickness and quality of the coal than could be secured by even a very large amount of diamond-drilling. In thin coal seams such as the Black Creek, averaging close to workable mining thickness with numerous thinnings and thickenings, drilling cannot be done in sufficient detail to prove their workable character over any considerable area, whereas by prospecting the outcrop thin areas can be located and traced to their limits. In the southern part of the Warrior field, in the Brookwood district, the same advantage of surface prospecting over drilling exists, giving more dependable data on the average thickness of the coal and also much necessary structural data on the block faulting prevailing in this district, which vitally affect mining conditions.

The field geologist with a coal-prospecting party must map the outcrop in advance as far as this can be determined, locating any important structural features such as folding or faulting that may affect the seam and interfere with the direct tracing work of the party. He must be familiar with all previous prospecting and mining data available on these seams and he determines the number of cuttings and the amount of tracing work necessary. The amount of detail required in such prospecting depends on the importance of the seam based on its thickness and probable time of future development, the degree of uniformity of section and the amount of structural irregularities. Our field mapping has been mainly done on a scale of 500 ft. to the inch, similar to the scale adopted for the land-section plats of this company, which has also been generally used on other geological mapping, and the final detailed maps are prepared on the same scale, including blocks of three sections square for convenient map size. The general areal maps, which comprise usually one or more townships, are drawn on multiple reductions of this scale to 1000 or 2000 ft. to the inch.

One of the basic requirements of the geologist with a coal-prospecting party, and in many other phases of economic work, is mapping the work

in the field, usually pacing distances and platting the work in his notebook or on plane-table sheet. These field maps of any coal-outcrop area with complicated geologic structure give a good index of his ability on any class of economic work and the keenness of his observance of essential details. It has been our experience that difficult geological structural problems have been solved, not by superior thinking, but by detailed painstaking mapping of the area, often continued to a point where it seemed impossible to secure further information.

Structural Prospecting in Pratt Coal Field

In the coal prospecting it was early found that all faults even of minor importance could be definitely located by tracing coal seams when pres-

Fig. 2.—Small area of the Pratt field covered by structural prospecting.

ent, and regardless of size, into the fault from both sides and test-pitting the coal directly on the fault plane. In this way the direction and dip of the fault and the displacement of beds can be determined. By tracing

and test-pitting small outcropping coal seams or markers overlying the Pratt group all faults of importance encountered in the mines have been located on the surface and their extent beyond the workings determined. Any additional faults in areas in advance of present workings have been located in the same way. On Fig. 2 is shown a small area of the Pratt field covered by such structural prospecting, underlain in part by Pratt mine workings and in part in advance of mine workings. By the prospecting work on the Cobb seam and Thompson Mill seam, which lie approximately 300 and 500 ft. respectively above the Pratt, the fault *A* of the mine is located on the surface, and its extent determined beyond mine workings. In the unmined area other faults, *B* and *C*, of similar size and extent have been located, and the dip and actual displacement on the surface determined. Such surface data have been proved to be closely representative of the character of the faults on the Pratt seam.

By means of outcrop structural prospecting of this type, with elevations on all pits and on many additional points on the outcrop, and with definite data on the Thompson mill-Cobb-Pratt interval from numerous drillholes, it is possible to contour the Pratt or other underlying seams, to which the interval is known, with surprising exactness. The displacement in the Pratt field on faults located on the surface as compared to the same faults 300 to 500 ft. below in the mine workings shows practically no variation, and the underground location of the faults also checks closely with that indicated by their dips at the surface. Due in part to greater variation in the thickness of intervening strata, equally accurate structural data on underlying seams are not yielded by surface prospecting in other areas.

Cahaba Field Prospecting

The prospecting of the Cahaba coal field has been one of the major duties of this department. The work consisted entirely of surface prospecting and test-pitting, with geological mapping and supervision, and extended practically continuously throughout the entire length of the field.

As shown on Fig. 1, the Cahaba coal field is a long narrow belt of coal measures in general steeply dipping. The dips throughout the main belt of coal outcrops average from 25° to 30° to the east, and gradually flatten down the dip. The thickness of strata is much greater than in the Warrior field, owing to the inclusion of a much greater proportion of sandstone and conglomerate. There is also greater variation in the coals. The number of workable coal seams, some 15 to 20 of economic importance, is approximately double that of the Warrior field. Structurally this field is also more complicated than the Warrior. Faulting and folding of major importance occur throughout and divide the field into separate basins. Because of continual variation in individual coal beds and in the

character of the intervening strata, and because a shale top often changes within a few hundred feet to massive sandstone or conglomerate, or vice versa, surface prospecting has been the only satisfactory method of proving the coal beds and determining the structural conditions affecting future mining operations. Diamond-drilling has been unsatisfactory except close to the outcrop, where the seams can be definitely identified from surface condition.

Utilization of Prospecting Data

Reports have been prepared covering all of the important subdivisions or coal basins of these fields. They summarize the data for ready reference and include estimates of the recoverable coal tonnage for each seam average analyses of the coals, cross-sections showing structural conditions probable limits of workable coals, etc. A comprehensive report of thil character based on definite field data is almost invaluable, not only fo possible future company mining operations but in connection with coa leased or sold to other companies, or with general exchanges of coal acre age to block up ownerships. The importance of the coal prospecting and its close relationship to the mining industry is indicated by the number of large mining operations now located in the prospected areas that were at the time entirely undeveloped, both in the Cahaba and in the northern part of the Warrior field. The importance of summarizing all prospecting data into a comprehensive report cannot be overemphasized. How often are prospecting data of different periods and under varying personnel filed or stored away on miscellaneous blueprints with no attempt at correlation, until they are entirely lost or forgotten. There could scarcely be a greater waste of money than that spent on prospecting or drilling without careful supervision, which often causes erroneous correlation of seams and leads to serious losses in future mining operations.

Because of the possession of such detailed data and intimate knowledge of the mineral deposits of the company, the geologist is in most cases in close contact with, or in direct charge of, leases of raw materials not required for future company operations. Such leasing operations are of large and growing importance for a corporation with large mineral acreage, portions of which may not be required for its own reserves. In general, after such a lease has been consummated, the geologist's relationship to the operation is very similar to that with his own company's operations.

With dependable estimates of the recoverable tonnages and character of the entire available reserves, the geologist, in close cooperation with the mining department, is in a position to advise his company as to the proper balancing of the reserves, the sale or lease of certain tonnage, or exchanges for more desirable acreage. The working out of equitable exchanges of acreage, required in blocking out separate holdings for satisfactory mining

operations, is an important phase of the geologist's duties. To properly appraise the value of interlapping mineral acreage in Alabama coal or ore fields with their varying conditions in mineral deposition, and with complicating structural difficulties, involves every possible phase of prospecting data and knowledge of mining conditions. The personal element is also important here in negotiations with outside companies, and permanent results can only be secured on an open and "above board" basis with no suspicion of sharp trading.

Prospecting the Clinton Red Ore by Diamond-drilling

As shown by Fig. 1, the red ore territory of greatest importance covers a relatively small area of possibly 100 square miles near Birmingham on the east side. The Clinton formation outcrops along Red Mountain and dips rather steeply to the southeast beneath overlying Mississippian strata, the thickness of cover increasing to above 3000 ft. under the crest of Shades Mountain, approximately 15,000 ft. from the outcrop. The Big Seam, the only seam of commercial importance, extends on the outcrop in workable condition from the vicinity of Birmingham to Raimund mines, a distance of approximately 15 miles; the outcrop following the crest of Red Mountain in a northeast-southwest direction, and to the east down the dip of the beds an indeterminate distance, in places exceeding several miles. The principal mining operations are all located in this belt, and, with the exception of the Shannon shaft operation, consist of slopes driven down the dip from the outcrop to a maximum distance of 5000 to 8000 ft.

The prospecting of the main Clinton red ore field in advance of mining operations to determine the character of the ore has been almost entirely by diamond-drilling, the closely spaced mining operations furnishing complete data on the ore adjacent to the outcrop. In areas adjacent to mine workings, or in connection with future operations the drilling has been done in close cooperation with the mining department. In most cases the drilling has followed the projection of present or future slope lines with the holes located to give structural data on fault zones as well as to prove the character of the ore. On undeveloped red ore acreage beyond mine workings, drillhole locations have been made to determine the thickness and character of the ore over as great an area as possible with the minimum footage of drilling. Because of the excessive depth of the seam in this advance territory, and the extreme hardness of overlying strata such as the Fort Payne chert, the maximum possible results must be secured from each drillhole. As in the coal drilling, a detailed record is made, and owing to the larger number of formations, the more unusual changes in sedimentation, and more complicated structural conditions, detailed checking of dips and evidence of faulting is required to an even greater degree. Every red ore drill

record, on which so much depends both in regard to ore conditions and for structural data on formations, intervals, dips, etc., must be complete and accurate in every respect. In most cases the complete cores from this Shades Valley drilling have been preserved and have proved valuable in checking up doubtful structural points, and also the conditions of various formations, which have in places developed economic value for limestone, sand, water, etc.

Structural Red Ore Mapping

As previously discussed, another important function of the geologist is the determination of the structural conditions of the orebody in advance of mining. In contrast to the Warrior coal fields where structural conditions can be worked out exactly by prospecting overlying coal seams, the structural conditions in the Shades Valley red ore territory are complicated and in many instances impossible to determine with the degree of exactness hoped for or expected. However, the necessity of such geological mapping is even greater in this field than in the coal fields, owing to the large amount of folding and faulting and reversal of dips prevalent in it. Diamond-drilling alone may give an apparent dip that bears no relation to the actual dip. Examples of erroneous structural maps based only on a small number of drillholes are not uncommon.

In connection with present operations, geological work is mainly concerned with working out faults and folds or any unusual structural features to determine their trend and extent in order to forecast where the ore will be encountered in other workings. In connection with faulting, the position of the ore beyond the break and its probable structure must be determined so that mining operations can be extended without unnecessary rock drifting. The position of the ore immediately across a fault can be closely predicted by the geologist, but often underground diamond-drilling is necessary for the proper determination of the structure of the orebody far enough in advance for the proper planning of mining operations. On any of the faults encountered in the mine where the strata across the fault are exposed, the position of the Big seam usually can be estimated within a few feet from a detailed knowledge of the strata of the Clinton formation. The strata exposed by faults in the mines are usually confined to the Clinton formation or beds closely adjacent thereto, and limited to the strata within 150 ft. above or below the Big seam. A generalized but rather definite average section of the Clinton formation of the main red ore territory is shown on p. 304.

From our experience with these divisions of the Clinton, it is usually possible to identify even a small exposure across a fault in the mines. The most dependable markers are the Ida seam, the Pentamerous horizon and the volcanic ash beds. The Upper Ferruginous sandstone can usually be distinguished by the crinoid stems and the considerable thickness of

uniform ferruginous sandstone. Below the Big seam the three divisions of the strata down to the ash bed are also distinct, the middle division only containing the ferruginous beds.

Average Section of Clinton Formation, Main Red Ore Territory

	Thickness, Feet
Fort Payne chert, top	
Fine-grained sandstone and shales with thin beds ferruginous limestone	30
Upper Ferruginous sandstone, occasional limy bands with crinoid stems	35
Gray shale and sandstone	15
Ore, coarse, pebbly, siliceous. Ida seam	1 to 2
Lower Ferruginous sandstone with Pentamerous zone 1 ft. thick, 4 to 6 ft. below Ida seam	6 to 8
Sandstone and shales	24 to 28
Ore, Big seam	15 to 20
Gray shaly sandstone and shale interbedded	35 to 38
Ferruginous limestone and shale interbedded	20 to 25
Gray shale and limestone	25 to 30
Volcanic ash beds, upper and lower with 3 to 5 ft. parting; Massive limestone } Chickamauga	5

In many cases in Shades Valley, faulting follows a general belt or zone consisting of numerous parallel interlapping breaks, and it is necessary to establish definitely the structure of the ore beyond such a disturbed zone before any plan of mining can be determined. Drilling low angle holes to two or more points on the seam beyond the fault, from positions in the mine offering the best possibilities for driving through the break, has been our general practice and has given sufficient data to plat up the structure on a cross-section. Identification of the separate divisions of the Clinton strata, and continued surveys both of the degree of inclination of the hole and its direction, are necessary to the proper platting of the cross-section.

Another structural feature of the ore in certain areas that involves mining difficulties, especially in the low-dipping areas where the ore was expected to be practically flat-lying, is its irregular rolling topography, somewhat of the sink-hole type, with relatively steep-sided basins several hundred feet across and above 100 ft. in depth. Such structures prevent any regular system of mining development and cause steep grades and difficult haulage. The location of these basins can only be projected to a limited extent from the contouring of the developed area, and they show no relation whatever to the overlying formations, so that they cannot be located from the attitude of the surface strata.

In structural mapping of undeveloped areas the diamond-drilling data have been supplemented by mapping the overlying Mississippian formations. Each formation was subdivided as far as possible into

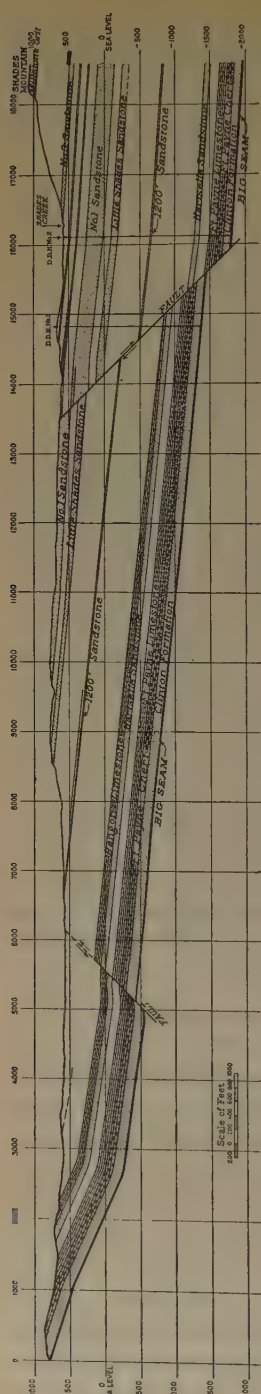

FIG. 3.—GEOLOGICAL CROSS-SECTION, NO. 7 RED ORE SLOPE LINE.

stratigraphic units. In addition to the general mapping, much detailed tracing, with prospecting, has been done on key beds, especially the sandstone horizons in the upper part of the Floyd shale and in the Parkwood formations. These horizons have been followed as far as possible by mapping the outcrops, but test-pitting has been used in important areas where the outcrops are covered. Where faulting was suspected or known to occur, the key bed was traced into the fault by test-pitting in a manner similar to that described with coal seams in the Pratt field, to determine its direction, dip and amount of displacement at the surface.

The faults in the Shades Valley red ore area are strike faults, and parallel rather closely the strike of the formation outcrops, which greatly increases the difficulty of locating them. They are practically all normal faults, overthrust faults being few and of small displacement in contrast to the overlying Cahaba coal field on the east, where the predominately important faults are overthrusts. The amount of throw or displacement, usually down on the east side, varies from a few inches up to a maximum of over 400 ft.; and the extent of the faults is usually roughly proportional to the amount of throw, faults of 100 ft. throw commonly extending from one to two miles in length. In general, the dip of the faults varies from 45° to 70°, although dips as low as 30° occur on minor faults which parallel and probably split off from the larger breaks. The dip of the faults is variable, steep, and even vertical in the harder formations; often decreasing to a low angle in the soft shales.

By means of the mapping of formations and key beds, the important faults of the area have been located and their surface features determined. However, the correlation of surface faulting with that on the red ore some 1000 to 3000 ft. below; or vice versa, the location of faulting encountered in the mine on the surface,

has proved a difficult problem especially with the smaller faults. The larger faults usually affect the formation outcrops sufficiently by offsets, thinning or thickening, etc., to be easily located, but smaller faults entirely within a formation may fail to be recognized by even the most painstaking mapping.

A representative geologic section across Shades Valley, showing the geologic formations, key beds and examples of important faulting, is shown on Fig. 3.

Special Examinations and Reports on Mineral Properties

One of the most interesting and important branches of the work of the mining geologist is making examinations and reports on various types of mineral properties. With our department, examinations are mostly of undeveloped properties offered to supply materials for some phase of company operations, including especially iron ores, coal, fluxes, manganese, fireclays, etc., but special examinations have been required on practically all varieties of mineral deposits. In the great majority of cases even a preliminary examination is sufficient to prove certain deposits to be of no economic importance. But if an undeveloped deposit shows some promise, the mining geologist's preliminary examination, frequently made at a time when few prospecting data and only very general inaccurate maps are available, requires experience and judgment, with some knowledge of mining conditions at other points in the district; and always necessitates an open mind with due respect for unbiased local opinion and knowledge. The fact that the great majority, possibly 99 out of 100 of such deposits investigated, prove noncommercial should put him on guard to an even greater degree to see that he does not condemn the one of value.

If the geologist recognizes the one "pearl of great price" among many mineral deposits, his relation to the mining industry becomes more intimate. Detailed prospecting work is required, usually by test-pitting and diamond-drilling under geological direction; and the nature of the orebody is determined in sufficient detail for estimates of tonnage and the proper planning of mining operations.

We have listed reports and examinations separately. Most examinations, even of the cursory kind, are accompanied by a report. But the mining geologist must write many of his reports on properties he has not examined, depending on published geological reports for his data. Any geological department, especially of a mining company with varied requirements in raw materials, must act as a clearing house for general mineral inquiries of which most are unimportant but which occasionally lead to something of value, such inquiries being received from all branches of the company operations and from countless outside sources in regard to mineral deposits in every part of the country. The geologist cannot investigate all these deposits himself, but must depend on published

information, principally the publications of the Federal and State Geological Surveys, covering areas in which they occur. The writer wishes to express herewith the deepest appreciation for these valued publications, without which this department would be seriously handicapped. Also in personal contact with visiting geologists and mining men from these bureaus we have received at all times the utmost cooperation and additional detailed dependable information of great value, especially in reference to iron ores, manganese, fluorspar and other materials essential for steelmaking.

General Activities

The geologist's contacts extend in some lines to practically all departments, and not only has variety given zest to his calling, but through such varied duties his work has increased in interest and importance.

In this department, outside of his mining activities, the geologist—owing to his intimate knowledge of the existing operations and of the available supply of raw materials—usually has close contact with the purchase of such items as iron ores of special grades, manganese, fluorspar, fireclays, etc., which may not be available from the company's operations. He may also, in many cases, with proper cooperation from both purchasing and operating departments, develop supplies of raw materials on company lands to take the place of materials now purchased from outside parties, or assist in the sale of waste products from company operations. By developing cheaper sources of supply for even relatively unimportant materials such as molding sands or clays, savings may be effected which will cover the entire cost of his department. One of the chief mineral products of interest in this sedimentary field is oil and gas, and in Alabama, although there is no commercial production, activities in the development of these have been increasing and are a matter of interest to all companies with large reserve acreage.

The Geology of the Iron Deposits of the Sierra de Imataca, Venezuela

By Guillermo Zuloaga*

(New York Meeting, February, 1934)

The iron deposits of the Imataca Range of Venezuela, which occur along the Orinoco River, in the northern border of the Guayana Highlands, have lately attracted attention on account of their economic possibilities. Many deposits occur in this area; some of slight economic importance and others that may rank with the largest masses of high-grade iron ore of the world. The geology and the character of the ores seem to be remarkably similar to those of the large iron deposits of Brazil.

In the investigation of the Venezuelan deposits a definite relationship has been found between the mineralization of the large orebodies and igneous intrusions, especially norites and granites.

The following paper is the result of a field and laboratory investigation of the ore deposits. The field work was done during the months of February and March of the year 1929, partly in the company of Prof. W. H. Newhouse. The laboratory studies have been made in the Massachusetts Institute of Technology, under the supervision of Professor Lindgren and Professor Newhouse.

GENERAL GEOLOGY OF GUAYANA HIGHLANDS

General Geography and Physiography

The Sierra de Imataca proper occupies a narrow belt along the south bank of the Orinoco River, in the northeastern part of the State of Bolivar and in the western part of the Delta Amacuro Territory of Venezuela. The State of Bolivar is generally known as the Venezuelan Guayana, as it forms part of the same physiographic province of the Guianas and northeast Brazil.

In general the Venezuelan Guayana is an extensive plateau, sloping gently towards the Orinoco River to the north and towards the Atlantic Ocean to the east. In the northern part mountains are rare, and consist mainly of elongated low hills. Towards the British Guiana-Brazil boundary, table mountains with vertical cliffs are found forming the ranges of Parima, Roraima and Pacaraima.

General Geology

The Guayana Highlands are the northern extension of the Brazilian Archean shield. Only a few scattered masses of sediments remain on its

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peneplained surface, and, in general, the landscape is structureless. See Fig. 1.

Archean Complex

The Archean complex is composed entirely of schists and gneisses eroded to a flat surface. Outcrops are abundant but inconspicuous.

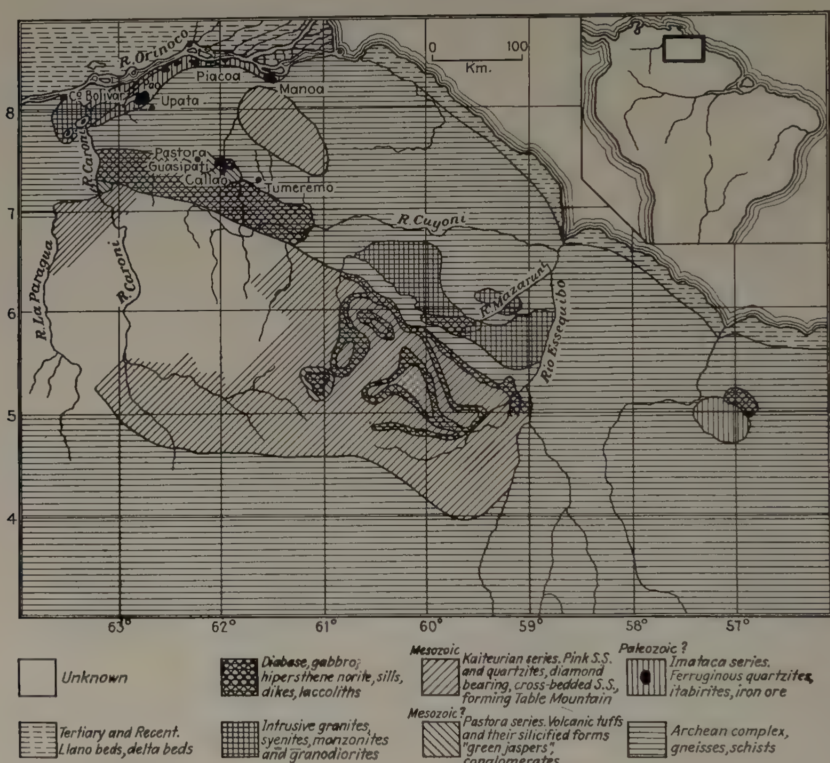

FIG. 1.—GEOLOGICAL MAP OF THE GUAYANA HIGHLANDS.

The gneissic structure in the area studied has a tendency to trend northeast.

No careful study has been made of the Archean complex. The most abundant rock is a buff colored gneiss in which pegmatite and aplite dikes are found. Lens-shaped masses of quartz are common, which sometimes carry gold. In places dark hornblende schists cover large areas. Mica schists were seen near Cicapra. Many younger intrusives appear in the complex.

Sedimentary Rocks

All age determinations of the sedimentary rocks of the Guayana Highlands are necessarily doubtful, as fossils have not been found in

them. Similarity to formations of known age in Brazil and mutual relationship have been the principal criteria used for correlation. The formations represented are listed in Table 1.

TABLE 1.—*Formations Represented*

NAME	COMPOSITION	AGE
Llano beds	Loose sands	Tertiary and later
Delta beds	Sandstones	
Alluvium	Gravels	
	"Moco de hierro"	
Kaiteurian series	Cross-bedded sandstone	
	Pink quartzites	
	Conglomerates	Cretaceous
	(Diamantiferous)	
Pastora series	Volcanic tuffs	
	Green jaspers	Cretaceous (?)
	Conglomerates	
	Dolomitic shales	
Imataca series	Ferruginous quartzites	
	Itabirites, iron ore	Early Paleozoic (?)
Archean complex	Schists and gneisses	Pre-Cambrian

Imataca Series.—DISTRIBUTION.—The oldest series of sediments found above the Archean complex is the Imataca formation of ferruginous quartzites, itabirites and iron ore. It is confined to the northernmost border of the Guayana Highlands, on the edge of the Archean shield, and forms a narrow belt along the Orinoco River. The Imataca formation must lie in places directly on the Archean complex, but igneous intrusions have obscured the contact.

Ferruginous quartzites similar to the Brazilian itabirites constitute the bulk of the formation, the only other rock found being iron ore.

In general there is little folding except large open folds or regional dips; closely plicated areas are of only local occurrence, being generally found very close to the intrusives.

The strike of the formation is about N.70°E. from Monte Cristo to Piacoa, a distance of 150 km., with the exception of the local disturbances at Pao and Los Castillos caused by the intrusions. The dip is in general to the south, averaging about 45°. From Piacoa east the strike turns east-west as far as Manoa where the delta covers the formation.

The maximum thickness of the Imataca formations appears to be about 200 m.; the height of the peneplain surface is about 100 m. above the level of the Orinoco. The formation is not continuous along the strike, but is rather a series of patches separated by broad valleys. A parallel ridge to the south, seen in places, may be another ridge of the formation separated from the first by subsequent valleys.

Locally, the iron deposits are found; they range from small masses a few inches across to masses with many million tons of high-grade ore. The change from itabirite or ferruginous quartzites to ore is not gradual but rather abrupt. The itabirites are, in general, very well banded (Fig. 2). Grain size is very uniform, averaging 1 mm. to the grain.

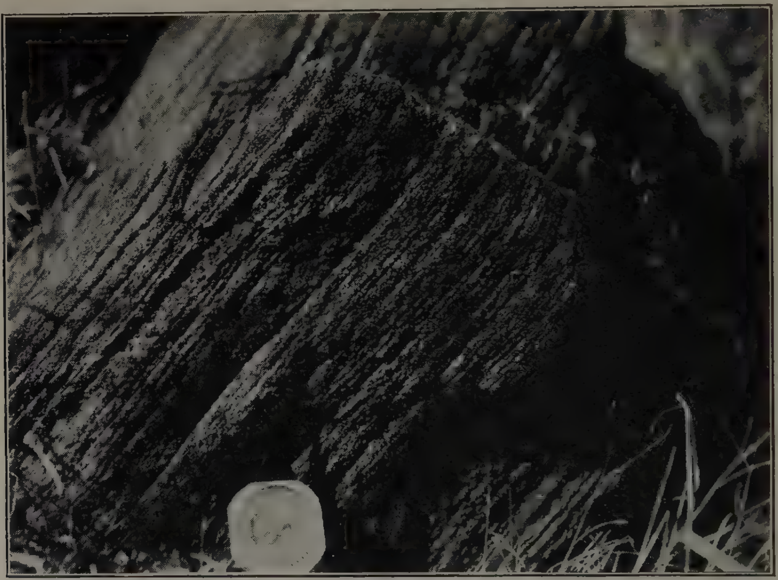

Fig. 2.—Outcrop of Imataca iron formation, Piacoa.

Neither shales, limestones, or other sedimentary rocks have been found with the quartzite. No cross-bedding or ripple marks were seen, and if present must be rare; this is a remarkable and puzzling fact. Close to the intrusive all banding is generally lost, and the grain becomes coarser; instead of breaking along the bedding planes the rock breaks with a conchoidal fracture. In general there is a marked uniformity of composition of the itabirite or iron formation; a thin section of the Monte Cristo quartzite is difficult to tell from one of Piacoa 150 km. away or one from Imataca 200 odd kilometers away.

Quartz, magnetite and hematite are the main constituents of the formation (Fig. 3). Minute grains of apatite are seen in the thin sections, but whether they are original or introduced by the intrusives cannot be said with certainty. In places, especially at Piacoa, hedenbergite is puite abundant in parallel bands, which cut the bedding at a low angle, qossibly following joint planes.

Under the microscope the minerals are found to be quartz, magnetite, hematite and goethite; more rarely hedenbergite, apatite, garnet (?) and possibly zircon. The proportion of these minerals is fairly constant; in

general it may be said that the itabirite runs close to 50 per cent metallic iron.

The quartz is quite clear, being rarely strained; no growth lines are shown and the grains are never rounded; they rather interlock like those of a granite. This may be due to recrystallization. Specks of magnetite are common inside the quartz crystals. The average size of grain may be a little less than 1 mm., although in places, near the intruding granite, it may be much larger.

The most abundant iron mineral is magnetite, and the data indicate that it was the primary iron mineral. The magnetite is rarely found alone; hematite almost always replaces it in tiny veins which work their way towards the inside of the crystals so that only skeletons of magnetite are left. The replacing hematite is in exceedingly minute crystals, which can be distinguished only with the highest magnification. This hematite does not, in general, follow any crystallographic direction in the magnetite (opposed to this the replacing hematite in the orebodies always does and gives pattern replacement) and everything seems to indicate that it is supergene and due to the action of surface waters on the magnetite. Crystalline goethite is the last iron mineral deposited; it replaces magnetite, but rarely the hematite. In some cases, minute flakes of specular hematite form the bulk of the iron oxide in the itabirite.

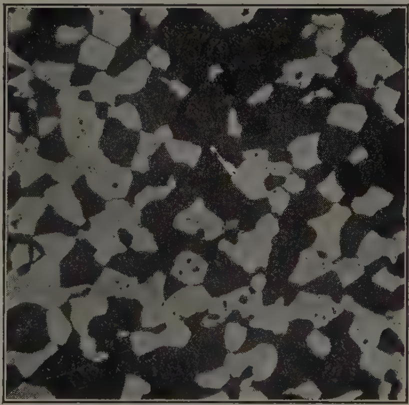

Fig. 3.—Thin section of Imataca quartzite, Piacoa. × 20. Quartz, white; iron oxides, black.

The important question arises as to whether all the hematite in the itabirites is supergene. The most typical thing about the ordinary supergene hematite is its occurrence as very minute veinlets, the size of the crystals being exceedingly small; yet in many cases there are bands and veins in the itabirite of coarse hematite.

But not all the veins of iron oxide that cut the bedding are of hematite; many are of magnetite. Crosscutting quartz veins are also common, although in general they are small and conform to the bedding. However, at the Imperial Hill, very near the contact with the granite, a large number of quartz veins cut the bedding.

Hedenbergite generally occurs in parallel bands, 5 to 10 mm. apart, which cut the bedding at a small angle, probably following joint planes. The crystals are emerald green in the fresh fracture, and may be as large as 5 mm. in diameter. The mineral is high in iron. Pleochroism is weak but noticeable. Apatite in places is abundant, and is widespread.

It occurs in slightly rounded prisms, and seems to increase in amount as the intrusive is approached. Cryptocrystalline silica, such as chert or jasper, was not seen in the Imataca formation.

Age and Correlation.—The age of the Imataca formation is doubtful. No fossils have been found. The remarkable similarity with the Itabira iron formation of Minas Geraes, Brazil, seems to be a very good reason for considering them equivalent and probably contemporaneous. Branner[1] puts the Itabira in the lower Paleozoic, mainly on stratigraphic indications. The best we can do is to correlate the two and call the Imataca lower Paleozoic.

Origin.—The Imataca series probably formed as a shore-line deposit. It is on the edge of the Brazilian shield, in a position very similar to the equivalent formation in Minas Geraes. Its distribution is like that of a shore deposit, and the uniformity along the strike can hardly be associated with any other type of deposit.

Pastora Series.—No formation was found to lie directly above the Imataca, but next in order of age comes the Pastora series. This is a series of green andesitic tuffs, several hundred meters thick, with some conglomeratic beds ending in bluish dolomitic shales. It is named after the town of Pastora, near which some very good outcrops of the tuffs are found.

The age of the Pastora series is unknown; it is probably much later than the Imataca series, and as it is closely followed by the Kaiteurian series, of probable Mesozoic age, it has been tentatively placed there.

Kaiteurian Series.—The youngest important group of sedimentary rocks found in the Guayana Highlands is a thick series of sandstones, pink quartzites and conglomerates of probable Mesozoic age. This is an extensive formation in the area near the boundaries between British Guiana, Venezuela and Brazil, where it forms an important group of mountains often bordered by precipitous cliffs. The formation has been named the "Kaiteurian series" by the geologists[2] of British Guiana.

Distribution.—The Kaiteurian series forms on an extensive belt from the Orinoco River near the Casiquiare, northeastwards toward British Guiana. Mount Duida and neighboring hills are composed of these sandstones;[3] also the Roraima and the Pacaraima mountains.

Age and Correlation.—The Kaiteurian series is probably Mesozoic. In Brazil it is mapped by Branner as Cretaceous,[4] although the evidence may be rather weak. No fossils have been found in it, but it seems to be

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[1] J. C. Branner: Outlines of the Geology of Brazil. *Bull.* Geol. Soc. Amer. (1919) **30,** 204.

[2] B. Smith: Report on the Preliminary Geological Survey of British Guiana, Georgetown, 1927.

[3] The Cerro Duida River of Venezuela. *Geographical Rev.* (Jan., 1930).

[4] J. C. Branner: Reference of footnote 1. Map and accompanying discussion.

undoubtedly younger than the Paleozoic series found farther south in the Amazon syncline.

Younger Sediments.—The Tertiary and Quaternary sediments of the Llanos are the main formations younger than the Kaiteurian, but they do not exist in the Guayana Highlands, with the possible exception of a small area south of Ciudad Bolivar.

Igneous Rocks

Igneous intrusives are common throughout the Guayana Highlands. The two most abundant groups of these rocks are granites and gabbros, although intermediate types are found. It seems probable that the granites and the gabbros belong to the same period of igneous activity.

The distribution of the intrusives on the geological map (Fig. 1) shows two striking relations. First, they occur in a belt running roughly parallel to the Atlantic Coast; and second, the basic and acid intrusions are always close together.

During the field work, it was seen that in many places there is a gradual transition from the acid to the basic rocks. The area of igneous intrusives in the neighborhood of the Pao orebody is especially interesting in this connection. In this section, granites change into monzonites, granodiorites or gabbros in a few hundred meters. Crosscutting bands of basic rock are found in the granite, and finally, as the orebody is approached, the rock becomes a dark even-grained hypersthene norite. A somewhat similar case is found near the Manoa iron deposit, where the granite changes suddenly into norite as the iron body is approached.

The data indicate that the norite was a separate intrusion coming soon after that of the granite, and possibly along the contact with the sediments. The granite may not have been completely consolidated and the transition rocks are due to mutual assimilation. Evidence for this is abundant and will be described later.

Granitic Group.—In this discussion only the rocks connected with the ore deposits will be considered.

(*a*) Typical Granite.—Characteristic granite connected with the iron deposits. It outcrops below the Imataca series. The rock is a medium to fine-grained granite of pink-brown color. In places it shows a slight tendency to be gneissic; this generally happens close to the contact with the Imataca quartzite. Microcline feldspar showing the characteristic twinning is the most abundant mineral. Granophyric structures are sometimes present. The quartz is generally clear, crystals are irregular and in places show crushing and strain effects. Biotite is the only mica found in any amount; generally it is dark greenish brown and very pleochroic. Accessory minerals are magnetite, apatite and zircon. The apatite is in slightly rounded prisms; the crystals are more abundant

and larger than usual in the samples from Monte Cristo, all of which are close to the contact. The same may be said of the zircon.

(b) Granitic Rocks of Pao.—The igneous rocks in the neighborhood of the Pao iron deposit present complexities which are not found in the rocks connected with the other iron deposits. There is an intrusive mass of norite between the Imataca series and the granite, which runs parallel to the strike; that is, northeast for some 10 km. Apparently owing to this basic intrusion, the granite has changed somewhat in composition, and very peculiar rocks are found. There is little doubt that the norite has intruded the granite, and that, at least in part, it has been the cause of the changes in it.

Veins of diopside and hypersthene, the two principal minerals of the norite, become abundant in the granite, and with them oligoclase feldspar appears; more advanced stages show large masses of diopside and hypersthene in the granitic mass, and with them labradorite feldspar, giving the somewhat rare occurrence of labradorite with quartz. As the proportion of oligoclase to the original microcline increases, the rock goes through phases which may be called quartz monzonite and granodiorite; more advanced stages produce rocks that can hardly be given a definite name, being in part gabbros, with labradorite and diopside, and in part granite high in quartz. There is no doubt that the diopside, hypersthene and labradorite are in veins cutting the granite.

Microscopically the groundmass of these rocks appears very much like that of the granite, the only change noticed in the early stages of veining is the presence of oligoclase and small veinlets of diopside. The amount of oligoclase increases gradually, apparently in proportion to the increase of the amount of diopside and hypersthene. Granophyric structures of quartz and feldspar appear in the neighborhood of the veins.

The crosscutting veins are, in general, made up of diopside, hypersthene, biotite, magnetite and apatite. Diopside is the most abundant; it occurs in irregular, stout grains of a light yellowish green. Hypersthene forms the bulk of one of the veinlets; the crystals are much more elongated than those of diopside; they have the characteristic reddish pleochroism and parallel extinction. The biotite is dark reddish brown. The crystals are somewhat fragmented, and are generally associated with the magnetite. Magnetite in irregular masses is abundant in the veins, in places constituting about one-half the weight. The labradorite feldspar, in these transition rocks, forms very much larger crystals than the other minerals.

A gneissic rock, composed of pink microcline and quartz, is found near the orebody. In thin sections the quartz is very much strained and has undulous extinction and locally shows mortar structure; the microcline is also granulated. The relationship of this rock to the others is somewhat obscure.

As a matter of fact, the appearance is remarkably like that of a quartz hematite gneiss found near by (will be described with the ores), and in the thin sections the quartz has identical characters. It may be possible that some of the hematite gneiss is due to replacement of the feldspar of this rock by hematite. The field relations, although not fully studied, seem to favor this view. Whether this gneiss is of igneous or metamorphic origin is difficult to say.

The Norite.—This probably is the most interesting rock from our point of view, inasmuch as the only two economically important iron deposits, Pao and Imataca, are connected with it. In these two places, the norite forms in part the footwall of the orebodies. It occurs in elongated masses between the granite and the Imataca formation. In the Pao area the norite was found along the strike for about 15 km. It strikes about northeast, being parallel to the Imataca formation. Little could be seen at Manoa to indicate the shape of the intrusion; its contact with the iron ore trends about east-west, as do the oreshoots.

Outside of these areas, no similar rock was found associated with the iron ores; granite alone is present in the other localities.

In general the norite is even-grained, the grains being about 1 mm. in diameter. It is almost black, with scattered specks of white feldspar. The samples from the drill cores are dark green, owing to the smaller amount of hornblende, which, in part, may be an alteration product.

At Imataca (Manoa) some samples of the norite are coarse and gneissic, with crystals up to 4 mm., but it seems to be local.

Megascopically few minerals can be recognized: black hornblende, white feldspar, iron oxide, and rarely specks of pyrite. The hypersthene has a luster like bronzite.

The rock is altering in places to serpentine. A serpentine rock found above the norite at Pao is probably such an alteration product. Burchard,[5] from determinations by Ross, calls the rock a gabbro. Because of the presence of hypersthene in large amounts, norite seems a more appropriate name. (See Fig. 4.)

In samples taken between Gibson bridge and the deposit, the feldspar is near the border line between labradorite and bytownite; it is positive like labradorite, but its index of refraction corresponds to bytownite, as does the extinction angle. The crystals are clear, often showing undulatory extinction. They are approximately equidimensional and many do not show twinning. The mineral comprises about 40 per cent of the rock. The pyroxene present lies somewhere between hedenbergite and diopside, but is closer to the latter. The crystals are rounded, and comprise over one-half of the dark minerals of the rock.

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[5] E. F. Burchard: The Pao Deposits of Iron Ore in the State of Bolivar, Venezuela. *Trans.* A.I.M.E. (1931) **96**, 355.

Hypersthene comprises a little under one-half of the dark minerals of the rock. The beta index is about 1.702, indicating extreme iron content, close to the pure $FeSiO_3$ molecule.[6] It has strong pleochroism, pink and green. Hornblende crystals are large, strongly pleochroic; and locally become fairly abundant. The beta index is 1.671. Part of the mineral may be due to alteration of the diopside.

The iron oxide, magnetite (?), present in thin section appears banded as ilmenite does sometimes, but no titanium test was obtained, and there

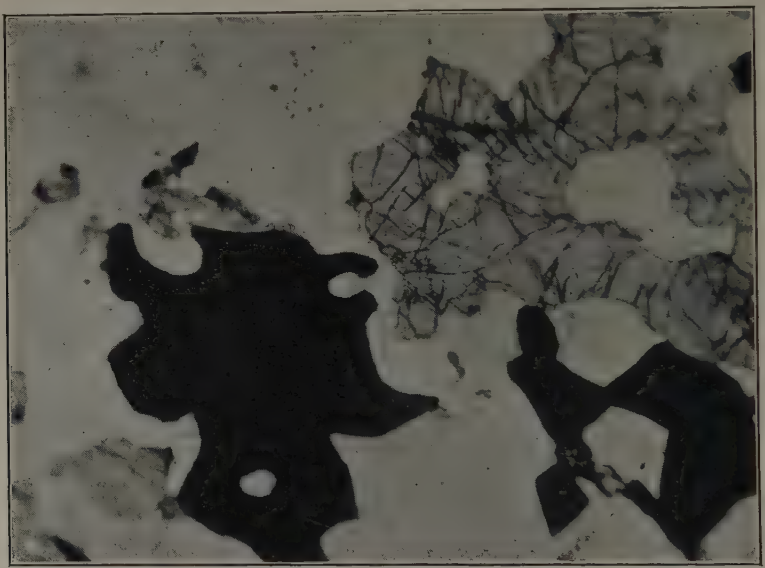

FIG. 4.—THIN SECTION OF NORITE, PAO DRILL CORE. ORDINARY LIGHT. × 34. Gray, hypersthene; black, magnetite; white, bytownite.

is no leucoxene in the rock, so it is probably magnetite. In some places it is fairly abundant, and increases as the iron body is approached.

Apatite appears in rounded grains, and has a tendency to cluster with the magnetite. It increases as the iron orebody is approached. A few small crystals of zircon are present.

In the hand specimens the norite from Imataca is identical with that of Pao; except that some very coarse phases are found here which were not seen at Pao.

THE DEPOSITS OF IRON ORE

Location and Distribution

The iron deposits of the Sierra de Imataca are in part in the State of Bolivar and in part in the Delta Amacuro territory of Venezuela.

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[6] A. N. Winchell: Elements of Optical Mineralogy, **2**, diagram on p. 177. 1927.

The Sierra de Imataca is a belt of low hills, ranging from 100 to 600 m. of altitude. It has been studied from a place called Monte Cristo, on the western side of the Caroni River, near the Rio Claro to the Orinoco delta, where the formation disappears. The Sierra de Imataca is made up of ferruginous quartzites of probably lower Paleozoic age. The iron deposits occur all along this formation, the quartzite itself running generally close to 50 per cent iron, so that eventually it may constitute an ore deposit in itself.

The area is in its greater part completely unexplored. The iron deposits that have been found, with the exception of those at Pao, are close to the Orinoco, where they are easily accessible, or in places where the motor roads have cut across the Imataca formation.

The deposit farthest west is at Monte Cristo hill, 30 km. southeast of Ciudad Bolivar, on the road to Guri, and 4 km. northeast of this is another hill, El Becerro. Both these localities are on the western side of the Caroni River. The next deposit known, Pao, is about 100 km. farther northeast, and about 50 km. from the Orinoco. The area between has never, to my knowledge, been explored by geologists.

About 50 km. north of Pao, on the southern bank of the Orinoco, are two outcrops of the Imataca formation, near a place called Los Castillos de Guayana. One of these, called the Imperial mine, was prospected by the Canadian Venezuelan Ore Co. two years béfore the World War, but no mining was done.

Piacoa is the next locality in geographical order; it is practically at the apex of the delta of the Orinoco. In this place also some exploration work was done by the Canadian company, the claims being called the Colon mines. From Piacoa, the formation outcrops here and there along the right bank of the Orinoco until the Imataca mines at Manoa are reached. This is the only locality in the area where any serious mining has been done; besides, it is the most accessible of the localities, being close to the sea.

Some other deposits, called La Escondida and Santa Catalina, are reported, but these localities were not visited and little is known about them.

The outcrops of the Imataca quartzite are generally covered by a heavy conglomeratic layer, the "canga," made up of fragments of ore and quartzite, cemented with iron oxide.

Classification of the Deposits

Of all the deposits just described, only one, or possibly two, have sufficient tonnage of high-grade ore to justify economic consideration at present. These are the newly discovered deposit at Pao, and the Imataca mines at Manoa. In these two places, there is a large tonnage of high-grade ore; in the others, the bodies of high-grade ore are small.

There seems to be a geological reason that causes the two deposits, Pao and Imataca, to be different from the others. They are connected with an intrusive norite, and they have igneous affiliations in their mineralization. This difference is also the probable cause of their richness. The other deposits are connected with granitic intrusions which have produced but little change in the ferruginous formations other than recrystallization and local concentrations.

We may tabulate the general characters of the deposits as follows:

I—Deposits in the Imataca quartzite, with recognizable sedimentary characteristics	II—Deposits in much metamorphosed rocks, probably of the Imataca series, with decided igneous affiliations
Monte Cristo	Pao
Becerro	Imataca mines, Manoa
Los Castillos	
Imperial	
Piacoa	
Intruding rock: granite	Intruding rock: granite norite
Small high-grade orebodies	Large high-grade orebodies in rocks of doubtful sedimentary origin. Mineralization largely by replacement of country rock.
Itabirite, in enormous volume running about 50 per cent Fe	

Although there are profound differences between these two classes of deposits, there are many points of similarity: they all occur in the same belt, and probably in the same formation.

Genesis of the Deposits

The Imataca sandstone was probably laid down as a highly ferruginous shore deposit. Whether the original iron was brought in solution or in suspension, there are, as yet, no data to decide; although the absence of chert or colloidal silica is difficult to explain if the deposition was chemical. Possibly there were rich places in the sediment, but, in general, the formation seems to have been remarkably uniform.

An intrusion of granite caused some migration of the iron in the sediments, redepositing it in fractures and places of easy circulation of solutions, in this way producing small bodies and veins of iron ore, such as are found at Becerro and Piacoa.

At Pao and Imataca, shortly after the intrusion of the granite, there followed an intrusion of norite which caused far-reaching changes, the metamorphosed quartzite and possibly in part the granite being replaced on a large scale by magnetite and hematite.

It is believed that the iron was not derived from the intruding norite, but that the iron originally in the itabirite was concentrated by the action of solutions accompanying the intrusion. The remarkable purity of the iron ores is noteworthy.

Deposits of Class I

Monte Cristo and Becerro

The hills of Monte Cristo and Becerro stand out about 250 m. above the level savanna, 30 km. S.20°E. of Ciudad Bolivar. They are made up of the Imataca quartzite, which is more resistant to erosion and weathering than the surrounding igneous rocks.

Under the present economic conditions, these hills do not constitute ore deposits. Geologically they are very interesting, inasmuch as certain facts can be observed which may help towards the understanding of richer deposits of a more complex geology. Possibly the most important of these facts is the proof that the granite is intrusive into the Imataca quartzite, and does not simply underlie the formation. This is shown by a thick layer of garnetized rock found at the foot of the Monte Cristo hill, and which undoubtedly is due to contact metamorphism.

Of interest, also, is the occurrence of pockets or small masses of iron ore that cut the bedding of the itabirite. These are especially abundant towards the top of Becerro hill. The ore in these pockets is made up of coarsely crystalline hematite and magnetite. The masses have a tendency to be elongated perpendicular to the strike, and possibly represent mineralization in cross joints. No large masses of ore in place were seen.

The eastern slope of the Becerro hill is covered with a layer of canga, which may run 10 or 15 m. thick in places, making many thousand tons of ore.

The Imataca itabirite forms the bulk of these two hills; it strikes N.60°E. and dips steeply to the south. In general, the iron in the itabirite is in the form of magnetite, but some samples from Becerro contain specular hematite.

In the Monte Cristo hill very little itabirite in bedrock was seen due to the canga covering; but halfway up the hill, about 20 m. above the garnet rock, a layer of coarse crystalline quartz about 30 cm. thick was found, and another one like it a few meters higher up.

These two layers are parallel to the Imataca formation, and show bedding, but whether they are of igneous or sedimentary origin cannot be said with certainty. The quartz, which is in crystals up to 1 cm. in diameter, is strongly etched on the surface and in some cases is very opalescent and of a light blue color. In the thin sections little can be seen; the quartz is clear, and shows a little replacement by iron oxide.

The Canga Ore

There are two types of canga, the one from Monte Cristo being quite different from the one at Becerro. The first class is decidedly conglomeratic, with pebbles of varied material, quartzite, ore, sand grains, and so forth, and, in general, is high in clay; the cement is iron oxide, which

shows botryoidal and other colloform structures. This rock is either dark brown or red, and nonmagnetic. The second class, or Becerro canga, does not appear conglomeratic; it is largely made up of magnetite, probably from replaced fragments. Hematite, goethite and limonite are common, probably due to the action of surface waters on the magnetite. The rock has the appearance of a scoria; it is bluish black and has a tarnish like tempered steel. In the polished sections it is seen to consist of magnetite, of characteristic brownish tinge, replaced by hematite and

Fig. 5.—Imataca ferruginous quartzite from Imperial Hill. Scale in inches.

colloform crusts of some kind of limonite. This canga is not strongly magnetic, but polar. A curious fact is that the magnetite does not look fragmental. Canga similar to this was not found elsewhere.

Los Castillos and Imperial

About 140 km. down the Orinoco from Ciudad Bolivar are two old forts built during the Spanish régime. One is on top of a granite outcrop, and the other on an outcrop of the Imataca itabirite. The place is now a military post of the Venezuelan government.

A little over 1 km. farther down the river is a flat-topped hill, the "Imperial" mine, which was prospected by the Canadian Venezuelan Ore Co. before the war. The Imperial hill slopes down to the bank of the Orinoco. It is made up entirely of the Imataca ferruginous quartzite. Outside of a few small veins and canga no real ore was seen. On the other hand, if the itabirite itself ever becomes minable, the Imperial is by far the largest known deposit of it.

Geology.—At Los Castillos, a direct contact of the granite and the itabirite was seen; the main change found was a development of gneissic structure in the granite near the contact, and the itabirite becomes coarser grained and the bedding disappears. It becomes very hard and has conchoidal fracture. In thin sections it is seen to be rather high in apatite.

The granite appears to have lifted the itabirite, acting like a laccolith, so at this locality the strike is about north-south in the west hill.

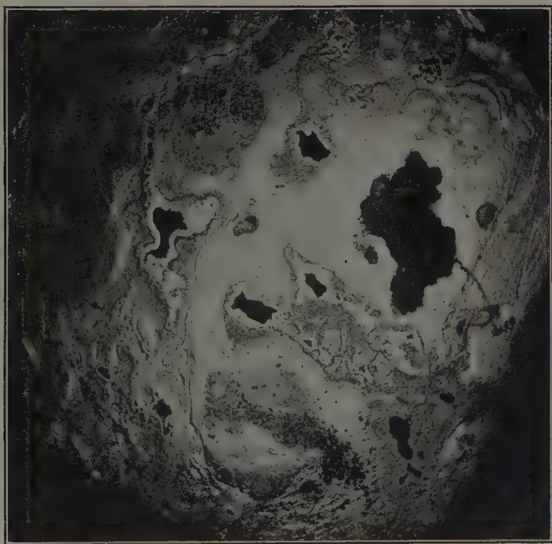

FIG. 6.—POLISHED SECTION OF CANGA ORE. COLLOFORM IRON HYDROXIDES. IMPERIAL. × 2½.

In the Imperial hill, near the base, which must be very close to the granite, many narrow quartz veins and closely plicated areas in the itabirite were seen. (Fig. 5.) The strike of the formation is again about N.60°E., parallel to the river.

The canga is present in large volume, but it is not as rich as that at El Becerro, and no magnetite is seen in it. It is mainly made up of iron hydroxides with colloform structures. (Fig. 6.)

A parallel range of hills is seen a few kilometers south of the Imperial and Los Castillos; it is probably formed by Imataca quartzite. The forest is so thick that it would be a matter of several days to reach it.

Piacoa

Piacoa is some 30 km. down the river from Los Castillos. Granite outcrops in the bed of the Orinoco at several places as the southern bank is approached near the Piacoa. The granite is slightly gneissoid, the structure running N.60°W.; that is, parallel to the river.

The Piacoa hills rise abruptly 4 km. south of the town of Piacoa, out of a flat savanna. The great depth of the Orinoco starts a short distance west of Piacoa, and delta beds form the flat savanna. In periods of much rain the Piacoa hills are an island above the river waters.

The Piacoa outcrop is elongated parallel to the Orinoco, this being the general strike of the Imataca formation. The strike averages N.60°W. and the dip is about 60°S.

There is little folding, the hills being cuestas; only a small cross fold was seen near the top, parallel to the strike. The top of the hills is the

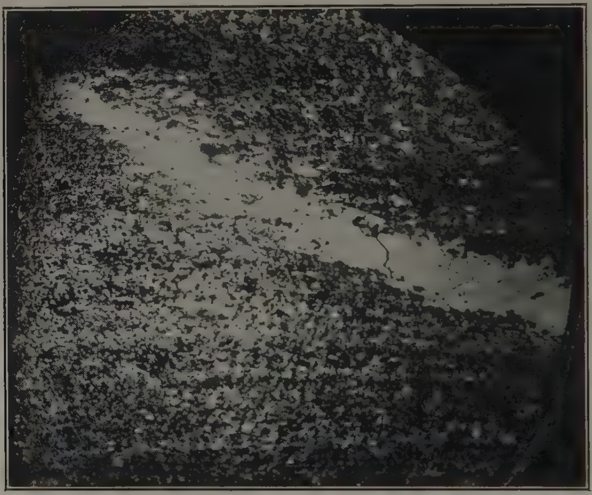

Fig. 7.—Polished section of Piacoa itabirite with crosscutting vein of hematite.
White, hematite; remainder, quartz.

remnant of a peneplain. This peneplanation was probably marine, and a cave found in one of the hills is probably due to marine erosion.

Little change can be noticed in the itabirite from the bottom to the top of the hills except that it is slightly coarser and higher in iron towards the base. Locally it becomes harder and carries hedenbergite. Halfway up the hill, magnetite and hematite veins are common. They were well seen along an exploration trench. Many of the veins conform to the bedding, others cut it (Fig. 7). The thickest vein seen was about 20 cm. of very polar magnetite, and in general the veins were so small that no actual ore was seen that could be mined, excepting possibly the canga.

In this connection the analysis and diagram given by Miller and Singewald[7] is of interest. From these analyses it is obvious that there is no ore here comparable to that of Pao or Imataca, which runs close to 70 per cent iron.

[7] B. L. Miller and J. T. Singewald, Jr.: Mineral Deposits of South America, 1919, 537.

The Piacoa canga is of two types: coarsely conglomeratic on the slopes, with fragments of ore and quartzite; and bedded ore of colloidal origin found at the top of the hill. Joints in the quartzite are generally filled with canga, which seems to be due to leaching of the silica by surface waters.

Deposits of Class II

Pao

The Pao orebody is the largest thus far found in Venezuela, and the only one that seems at present of sufficient importance to justify development. The amount of high-grade ore in sight is enormous.

The geology of the Pao deposit is very complex, and inasmuch as the field investigation made by the present writer was short, no absolutely definite statements can be made about the geological structure. However, in addition to the writer's personal investigation (which was made in company with Professor Newhouse) there has been added a paper by Burchard,[8] his personal communications to the author, and maps and drilling data obtained by a company that has partly prospected the area.

Geography.—The Pao orebody is on the top of a precipitous hill of about 650 m. altitude in the midst of the Imataca Range. The locality is about 50 km. south of San Felix, a port on the Orinoco River. The area is one of heavy rainfall, and inasmuch as the orebody is elevated, water circulates through it.

General Geology.—The lower parts of the Pao hill are composed of igneous rock, mainly granite and norite; above these are found the orebody and profoundly metamorphosed rocks, which probably are altered equivalents of the Imataca formation.

The orebody occupies the top of the hill; it grades in depth into a rock made of hematite and quartz, the ore undoubtedly being an advanced stage of the replacement found in this hematite gneiss. This is shown spatially because the ore grades not only in depth but along the strike into this siliceous ore, and the microscopic study shows that the iron oxide replaces the quartz, and that the structure of the iron oxide of the orebody and that of the hematite gneiss are identical.

Interbedded with the orebody and below the mass of siliceous ore is found a norite intrusive. The lower mass of this intrusive lies above the granite, and between the two, rocks of intermediate composition are found.

The strike of the structure of the hematite gneiss is about northeast and the dip is to the south steeply; the banded structure of this gneiss is preserved in the ore and the strike and dip are the same, this fact alone being good indication of replacement. The banding of the ore is one of

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[8] G. Zuloaga: The Iron Deposits of the Sierra de Imataca Venezuela. *Econ. Geol.* (1930) **25**, 99–101.

E. F. Burchard: Reference of footnote 5.

the most characteristic features of the Pao orebody. The ore at a distance looks like gneiss; large masses are of very fine-grained specularite with fine banding; in both cases the strike of the structure corresponds to that of the siliceous ore found on the way up, and the outcrops as well as the Pao hill itself are elongated in this direction, so it seems reasonable to suppose that this is the true strike of the formation, possibly the strike of the original Imataca quartzite which has been retained by replacement.

The siliceous ore is so metamorphosed that its origin cannot be determined with certainty; however, a large boulder of bluish itabirite was found near the lower camp, which appears identical with quartzite that outcrops on the road from Caruachi to Callao.

In summary, the sequence of events was that the Imataca formation was intruded by a granite and shortly afterwards by a norite, with strong accompanying metamorphism.

The Orebody.—Several orebodies outcrop in the neighborhood of Pao, particularly Gutierrez Hill, but the present investigation has been mainly of the orebody included between the so-called Boccardo and Picacho hills. The orebody outcrops on the west and east edges of these hills, the gneissic structure striking and dipping the same way in both outcrops (strike about northeast, dip about 45° southeast). Both outcrops have the appearance of *cuestas* or dip slopes.

The flat area between these outcrops is covered by canga and clay so that no bedrock can be seen. Diamond drilling revealed norite under this area, a rock similar to the one found outcropping farther down the slope of Pao hill.

Boccardo and Picacho outcrops are pyramidal masses of dense bluish hematite; enormous blocks and ore in place make a spectacular appearance, inasmuch as no gangue minerals are seen and the ore is of the highest purity. A large surface is covered with conglomeratic canga. The edges of the hill are precipitous cliffs cut in solid ore, possibly due to faulting.

The Gutierrez and other hills to the southeast are also made of ore, but no examination was made of them.

Form.—The form of the Pao orebody is not well known. From the field studies, the two hills Boccardo and Picacho are seen to strike and dip the same way, so that the norite found by drilling is possibly a sill between the two ore masses.

The diagram in Fig. 8 shows the structure of the Pao hill and orebody as it may be inferred from the field data. However, from the drill records, the orebody may be thought to be basin-shaped. Fig. 9 shows the orebody plotted from the drill records and the structure of the Pao hill if this is correct.

A basin shape for the orebody does not seem justified. It would imply a change in the strike of the structure along the outcrops, which is

not found (except local disturbances). On the other hand, from the shape of the Pao hill it can be seen that the general strike is northeast.

The thinner layer of ore found by the drill, between Boccardo and Picacho hills, is possibly due to the presence of horses of ore in the norite.

If instead of this basin-shaped orebody, there are two dipping the same way, the expected tonnage may be doubled.[9]

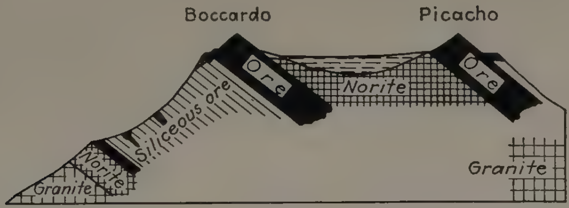

FIG. 8.—THEORETICAL NORTHWEST-SOUTHEAST SECTION OF PAO OREBODY ACCORDING TO PERSONAL FIELD WORK.

Serpentine and Ferruginous Clay

The layer of serpentine found between the norite and the orebody is probably a hydrothermally altered norite. Nothing has been found in the thin sections of this rock to justify calling it a decomposed peridotite,

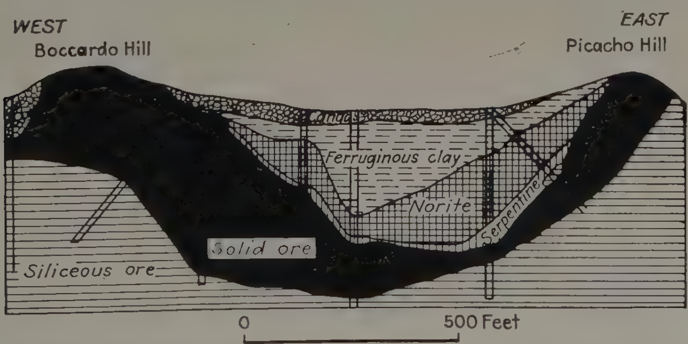

FIG. 9.—GENERALIZED CROSS-SECTION OF PAO OREBODY. FROM DIAMOND-DRILL HOLE DATA.

but, on the other hand, drill cores of the norite show the gradual serpentinization of the rock. The ferruginous clay is obviously the weathered part of the norite.

The Ores

Chemical and Mineral Composition.—The ore from Pao is of remarkable purity; with the exception of Brazilian ore, hardly any other can compare with it in quality.

The chemical analyses in Table 2, quoted from Burchard,[10] are taken as representative.

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[9] Recent information is that further drilling has proved this theory correct.

[10] E. F. Burchard: Reference of footnote 5, 361.

TABLE 2.—*Analyses of Iron Ore from Pao Deposits*

SURFACE SAMPLES, PERCENTAGES AFTER DRYING

No.[a]	Fe	SiO_2	Cu	Mn	Ni	Cr	Al_2O_3	As	TiO_2	S	P
A	68.00	0.36	None	0.27	None	None	0.09	None	0.12	0.01	0.051
B	69.25	0.38	None	0.09	None	None	0.33		0.08	0.02	0.028
C	69.05	0.46	None	0.08	None	0.08	0.28	None	0.20	0.027	Trace (less than 0.01)

[a] A. Composite of 13 samples taken on Boccardo Hill over a distance of 1400 ft.; average width of ore 76 ft.

B. Composite of 6 samples taken on Boccardo Hill over a distance of 800 ft.; average width of ore 360 ft.

C. Composite of 5 samples taken on Picacho Hill over a distance of 1000 ft.; average width of ore, 161 ft.

ORE FROM DIAMOND-DRILL CORE NO. 1, PER CENT

Depth, Ft.	Fe	Mn	P	S	SiO_2	Al_2O_3
35	71.33	0.03	0.020	0.028	0.09	1.97
50	68.14	0.03	0.024	0.029	0.16	3.29
100	68.75	0.03	0.020	0.112	0.09	2.65
150	67.81	0.05	0.030	0.118	0.05	4.04
200	69.74	0.03	0.023	0.099	0.13	1.01
250	70.73	0.12	0.028	0.067	0.10	1.03
300	68.86	0.02	0.013	0.048		
350	68.53	0.05	0.025	0.039		
400	68.20	0.04		0.08	0.56	1.30
420	67.52	0.03		0.01	0.64	3.17

In the following mineralogical discussion of the ores, the siliceous ore or hematite gneiss will be discussed with the ore because it grades into the orebody.

The mineralogy of the Pao ores is simple, as might be expected from the chemical analysis; practically nothing is present except iron oxide and quartz. The minerals of the ores are as follows:

Gangue Minerals:
- Quartz, in hematite gneiss; rarely as remnants in ore.
- Corundum, in bands with hematite, rare; as fragments in canga.
- Apatite, in hematite gneiss, very rare.
- Pyroxene (?) in hematite gneiss, rare, not identified.

Ore Minerals:
- Magnetite; probably the only hypogene mineral.
- Hematite, generally replacing magnetite.
- Specularite, in large crystals with basal parting; in finely banded ore.
- Goethite, $Fe_2O_3.\frac{1}{2}H_2O$, in crystals replacing magnetite and hematite; found mainly in drill cores.

Minerals in Canga Ore:
- Quartz, in crystals generally etched.
- Bauxite, pisolitic.
- Clay, probably decomposition product of norite.
- Corundum, one fragment found in canga, rare.
- Magnetite
- Hematite
- Goethite
- Limonite
- Manganese oxides (?)

Classification and Study of Ores

Three main types of ore can be distinguished at Pao: (1) siliceous ore (hematite gneiss); (2) high-grade ore; (3) canga.

Siliceous Ore.—Distribution.—The first outcrops of the hematite gneiss were found about 6 km. southwest of Pao, and from there the rock

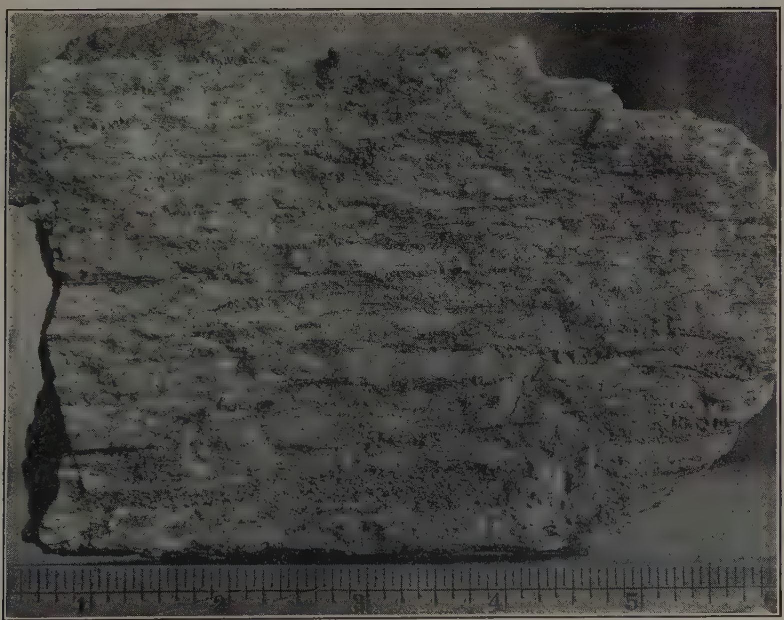

Fig. 10.—Hematite gneiss, Pao. Scale in inches.

can be followed almost to the orebody. In places it is interbedded with ore bands up to 1 m. thick; it grades along the strike into the main orebody. Some of the ferruginous layers, especially towards the bottom of the section, are honeycombed, owing to action of surface waters.

Megascopic Study.—The siliceous ore forms a rock of the appearance of a gneiss; it is made up of parallel bands of quartz and iron oxide, there being an average of 12 bands of quartz and 12 of iron oxide in 5 cm. (Figs. 10 and 11).

The proportions of quartz to iron oxide are variable. The siliceous ore is slightly magnetic, indicating that some magnetite is present with the hematite. The iron obviously replaces the quartz; in places the banded appearance is lost because of thorough replacement.

Microscopic Study.—The most striking feature of the siliceous ore in thin sections is the cataclastic structure of the quartz. In no other rock has the writer seen a duplicate of such crushing and fracturing; even flow structure is seen in some cases. Undulatory extinction is typical

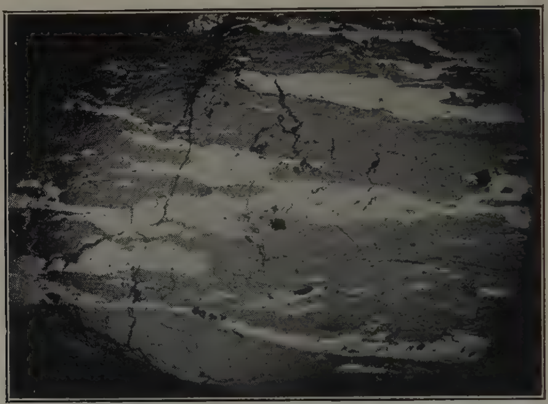

Fig. 11.—Polished section of hematite gneiss, Pao. × 2½.

of the quartz; the direction of the fractures shows that they are due to movement parallel to the gneissic structure.

Rounded fragments of a green pyroxene are seen in some of the thin sections, but the cleavage is not well developed and the optical properties not very definite; it looks like hedenbergite, but the determination is doubtful. One or two doubtful crystals of apatite were found.

The opaque minerals are an intergrowth of magnetite and hematite. With high magnification, the hematite polarizes strongly, and one set of parallel lines all extinguish at the same time like microcline feldspar. The hematite is of later deposition than the magnetite. It replaces the magnetite on the periphery of the crystals and works towards the center generally connected with fractures. Whether this replacing hematite is hypogene or supergene cannot be said with certainty; but it does not have the same appearance as the supergene hematite found in the itabirites.

Discussion.—It is believed that this siliceous ore is a much metamorphosed phase of the Imataca quartzite; both formations apparently are continuous and the composition is very similar.

Although the iron oxide has migrated and is of later crystallization than the quartz, it is quite probable that the iron oxide originally present in the itabirite was dissolved by solutions coming from the igneous rocks and redeposited replacing the silica.

A true gneiss, composed of microcline and quartz, is found near the siliceous ore, and shows structures of the quartz under the microscope which are very similar to those of the thin sections of the siliceous ore; in fact, it is possible that part of the rock may be such a gneiss with the feldspar replaced by iron oxide.

High-grade Ore.—In the following discussion of the ores, the ore from Imataca has not been included, as nothing different was found at that place and a separate description would be repetition.

The following variations in the high-grade ore can be distinguished:

1. Dense ore, medium-grained, bluish, with gneissic structure.
2. Like the former, but with much pore space and stronger banding.
3. Fine-grained specular hematite with good lamination.
4. Coarse-grained specular hematite with eminent parting, so that the mineral at first glance looks like galena.
5. Dense ore from drill cores, with no visible structure.

Ore of Class 1 is the most abundant ore in the outcrops; it forms the bulk of Boccardo and Picacho Hills. The color is steel blue, the ore is dense but with variation in crystal size. Gneissic structure is very prominent in the outcrops, but does not appear much in hand specimens. Magnetism is strong, in some cases quite polar.

Microscopic study shows that magnetite is replaced by hematite; the latter is the most abundant mineral. Some grains are of pure hematite, and show twinning of the unit rhombohedron. Quartz grains are occasionally found.

The hematite replaces the magnetite along crystallographic planes, producing cross-hatched structure. The hematite is related to fractures and probably is due to the action of surface waters (Figs. 12 and 13).

The primary mineral was probably all magnetite.

Ore of Class 2 is like that of Class 1 but with much pore space and stronger banding. It is of local occurrence and may be in part formed by much leaching by surface waters; it is nonmagnetic and is almost pure hematite.

Ore of Class 3 is composed of specular hematite with fine banding, and varies from very fine-grained to ore of class 1, nonmagnetic. This ore is most abundant near Boccardo Hill; the banding strikes like the structure of the siliceous ore and the gneissic high-grade ore; it is probably due to replacement, possibly to shear. The polished sections show very fine-grained specular hematite with occasional grains of magnetite. Hematite replaces magnetite.

Ore of Class 4 is coarse-grained specular hematite with eminent basal parting so that the mineral resembles galena. The ore is of local occurrence, and was found most abundantly in O'Callahan Hill. The crystals of hematite range up to 1½ cm. in diameter, with beautiful twinning; the parting in one direction coincides with the twinning, which

is in two directions of the unit rhombohedron. The parting is the same as that found in corundum, inasmuch as both minerals have almost identical crystal structure. This is probably the purest hematite found at Pao; it is only slightly magnetic.

Microscopic study shows that the hematite, owing to the twinning, has much the appearance of plagioclase feldspar in thin sections; the twins extinguish alternatingly. (See Fig. 15, p. 12, in Burchard's paper.) In some cases the laminae of hematite are so thin as to transmit light. The color is ruby red. No magnetite is seen in the sections.

Fig. 12.—Supergene hematite replacing magnetite along fractures, Pao. × 100.

Fig. 13.—More advanced stage of supergene hematite replacing magnetite along fractures, Pao. × 300.

Ore of Class 5 is dense ore from drill cores, with no visible structure. Pieces of drill core from Pao look like drill steel, except for occasional small cavities. The fresh fracture, seen with a binocular microscope, shows that the small cavities are vugs lined with crystals of specular hematite. Limonitic stains produced by goethite crystals are seen in the fracture.

Microscopic study (polished sections of drill core from 350 ft. depth, supplied by Mr. Pagliuchi) shows that the most striking feature of the polished sections of this deep drill core is the abundance of goethite in strongly polarizing crystals of a lead blue color. Inasmuch as goethite is a hydrated oxide and is seen to be connected with fractures, it shows the action of surface waters on the ore.

Hematite is still the most abundant mineral; it replaces the magnetite along crystallographic planes, giving a pattern of hematite lines at right angles in the magnetite. With polarized light, one set of hematite blades extinguishes simultaneously, showing that the hematite is oriented along crystallographic planes.

The age relation between the goethite and the hematite is obscure; the goethite rarely replaces the hematite but usually the magnetite, so that the hematite is left in a field of goethite, giving the impression that it may be later than the goethite. However, it is possible that some of the goethite is earlier than some hematite, particularly the hematite found lining the vugs. Both the hematite and the goethite appear supergene, inasmuch as they are related to fractures. The only hypogene mineral appears to be magnetite. The samples of drill core are less magnetic than the surface samples; only after very fine grinding can the magnetite be separated with a magnet. Why goethite is present in depth and not in the surface samples cannot be told with certainty; possibly in the outcrops the temperature and conditions of humidity are not favorable for its stability, while in depth, saturation with water and uniform temperature may favor its crystallization. No amorphous limonite is found in the drill core.

Canga Ores.—There are many variations in the canga of Pao; from a very coarse conglomerate of fragments of ore several meters in diameter cemented by iron oxide, to pure colloidally deposited hematite and limonite. In places the canga contains much quartz, the crystals of silica being etched. It is probable that this quartz had been liberated by leaching of the iron oxide in the ore. Pisolitic bauxite is abundant in places.

The canga mantle is mainly responsible for the flatness of the top of the hills. Its general aspect and the presence of bauxite suggests that it is the result of long weathering of the iron ore and the igneous rocks at base level conditions.

Marine peneplanation probably has taken place; the caves at Piacoa Hill are an indication of it, and pot holes and caves are abundant on Pao Hill.

General Discussion of the Ores.—From the study of the ores we can deduce the following facts:

1. The primary, hypogene, mineral seems to have been magnetite.
2. The magnetite is being replaced by hematite.
3. The hematite is usually connected with fractures and is very probably supergene.
4. The ore minerals are replacing the silica in the banded siliceous ore.
5. The orebody grades along the strike and in depth into siliceous ore.
6. The orebody is due to a thorough replacement of the siliceous ore shown by
   (*a*) Gradual change of one into the other;
   (*b*) Preservation of banded structure with same strike and dip.

From the field relationships it can be seen that:

1. The orebody is always in contact with norite.
2. The orebody fades away from the norite.

3. Inasmuch as the primary mineral seems to have been magnetite, so far considered a high-temperature mineral, the solutions that deposited the iron oxide or made it migrate in the mass of the quartzite were hot.
4. The norite is directly or indirectly the cause of the mineralization.

ORIGIN OF THE IRON.—The remarkable purity of the ore, especially the absence of sulfur and other impurities, such as titanium, generally found in iron ores of igneous or contact-metamorphic origin, seems to indicate that the iron oxide did not come from the norite, but rather was dissolved from the quartzite by solutions coming from the norite and was redeposited by replacement in favorable places, silica being carried away by these solutions.

That the iron did not come from the norite may be further shown by the fact that the proportion of iron increases in the norite as the orebody is approached, a fact that the writer believes to be due to assimilation of ferruginous material.

The absence of phosphorus in the ore and its presence in both the norite and the Imataca quartzite is puzzling. It may have been carried away by hot solutions.

This subject of the impurities may be seen in another light if we consider that the ore assays close to 70 per cent Fe, and that if it were chemically pure hematite it would assay 70 per cent Fe and 30 per cent O. Hence there is little room for impurities. Furthermore, if the proportions of elements to one another instead of actual amounts are considered, the amount of phosphorus and other impurities is explainable.

Imataca Mines at Manoa

Only a short visit was made at this locality. The Imataca mines are on the right bank of the Orinoco River, some 100 km. from the Atlantic Ocean, a short distance west of the Caño Corosimo, one of the distributaries of the Orinoco delta.

These mines are the only ones ever exploited for iron in Venezuela. They were worked from 1912 to 1914 by the Canadian Venezuelan Ore Co. From what can be seen in the field, and from information filed at the Department of Mines in Caracas by the Canadian Venezuelan Ore Co., the geological relations seem to be as follows:

Granite, which outcrops in the river north of the mines, grades into norite toward the orebodies; the ore grades into siliceous ore and finally into ferruginous quartzite. The deposit is then very similar to the one at Pao. The orebodies are tabular and in parallel beds, probably replaced sedimentary rocks. The orebody lies against the norite and fades away from it into metamorphosed quartzite.

These relationships seem to show that the norite is the cause of the mineralization. The position of the orebodies might even suggest

TABLE 3.—*Comparison of Chemical Analyses of Various Ores*

Reference No.	Ore	Iron	Phosphorus	Alumina	Sulfur	Manganese	Silica
1	Venezuela	68.8	0.02	0.23	0.02	0.15	0.40
2	Brazil	68.8	0.02	0.47	0.02	0.19	0.46
3	Gogebic	60.3	0.05	1.93	0.00	0.76	5.58
4	Lake Superior	59.6	0.06	1.50	0.02	0.30	7.50
5	Cuyuna	58.1	0.19	3.13	0.02	0.31	8.26
6	Chile	68.8	0.03	1.90	0.01	0.16	1.30
	SEDIMENTARY						
7	Lorraine	40.6	1.81	3.24	0.10	0.30	6.90
8	Clinton ore (Alabama)	36.5	0.33	2.79	0.97	0.21	10.72
9	Ohio-Pa. Carb	44.8	0.19	5.75	0.67	0.70	18.50
10	Clev. Hills, Eng	29.2	0.60	6.12	0.05	0.33	8.51
11	Wabana	53.8	0.85	3.55	0.01	0.65	9.48
	IGNEOUS						
12	Kiruna	64.4	1.20	0.40	0.03	0.08	1.90
13	New Jersey	61.0	0.90	0.77	0.01	0.04	8.46
14	Arnold mine, N. Y	62.3	0.23	1.72	0.35	0.24	7.64
	CONTACT-METAMORPHIC						
15	Iron Springs	56.0	0.20	1.00	0.05	0.19	7.00
16	Cornwall	64.9	0.14	0.32	0.71	0.15	3.98
17	Persberg	55.7	0.00	0.77	0.03	0.17	12.76
	RESIDUAL						
18	Mayari, Cuba	50.5	0.01	10.24	0.20	0.09	2.90
	BOG ORES						
19	Sweden	41.5	0.21	3.58	0.02	4.10	12.64
20	Quebec	45.0	0.30	2.59	0.07	0.91	13.94
	UNCLASSIFIED						
21	Donetz, Russia	44.4	0.21	6.86	0.17	0.60	18.24
22	Rudin-Kamak (Bulgaria)	40.0	0.04	0.000	0.04	1.50	31.10
23	Gossan Lead	41.2	0.64	0.00	0.13	0.30	9.74

1. Average of analyses of Pao ore from Burchard: *Trans.* A.I.M.E. (1931) **96.**
2. Average of first eleven analyses from Leith and Harder: *Econ. Geol.* (1911) **6,** 680.
3. Average of ore mined in 1906 from U. S. Geol. Survey *Mon.* 52 (1911) 238.
4. Average of cargo analyses for 1905 from *Imperial Mineral Resources*, Iron Ore (1922) Pt. 7, 74,
5. Average of many analyses given in U. S. Geol. Survey *Mon.* 52 (1911).
6. Pan de Azucar Mines. Eckel: Iron Ores, 303. 1914.
7. Average of Gray Bed, higher in Fe than average. *Imperial Mineral Resources*, Iron Ore (1922) Pt. 6, 38.
8. E. F. Burchard: written communication.
9. *Imperial Mineral Resources*, Iron Ore (1922) Pt. 7, 69.
10. W. Lindgren: Mineral Deposits, 308. 1928.
11. E. C. Eckel: Iron Ores, 65. 1914.
12. Average of analyses given in *Imperial Mineral Resources*, Iron Ore (1922) Pt. 7, 213.
13. Analysis (b) average for Elizabeth mine. *Imperial Mineral Resources*, Iron Ore (1922) Pt. 7, 57.
14. *Idem.*
15. *Idem*, 74.
16. Analysis of "niggerhead" ore. *Imperial Mineral Resources*, Iron Ore (1922) Pt. 7, 62.
17. W. Lindgren: Mineral Deposits, 836. 1928.
18. *Idem*, 379.
19. E. C. Eckel: Iron Ores, 50. 1914.
20. *Idem*, 50.
21. *Imperial Mineral Resources*, Iron Ore (1922) Pt. 6, 159.
22. *Idem*, 25.
23. *Idem*, Pt. 7, 42.

contact metamorphism, but the mineralogy of the ores rather points to concentration of the iron originally in the quartzite.

The following average analysis of three cargo shipments of iron ore from Manoa, quoted from Miller and Singewald[11] may be mentioned: metallic iron, 66.53 per cent; silica, 1.81; phosphorus, 0.031; sulfur, 0.045; titanium, 0.139. However, since much canga was mined and shipped with the ore the apparent grade is probably too high.

THEORETICAL CONSIDERATIONS

Origin of Venezuelan Ores Compared with Brazil, Lake Superior and Other Ores in Banded Rocks of Probable Sedimentary Origin

General Discussion of Theory

It has been considered advisable to compare the chemical analyses of the Venezuelan ores with iron ores of important occurrence throughout the world. For this purpose, representative average analyses from many ores have been compiled and arranged according to genetic groups. Certain ores of which the origin is still under discussion, or which are of great importance from our point of view, such as those of Lake Superior, have been considered in a class by themselves. See Table 3.

For average analyses of genetic groups, the average of those given in Table 3 have been taken, giving the results shown in Table 4.

Table 4.—*Average Analyses of Genetic Groups*

	Iron	Phosphorus	Alumina	Sulfur	Manganese	Silica
Sedimentary	40.9	0.75	4.29	0.36	0.44	10.84
Igneous	62.5	0.77	0.96	0.13	0.12	6.00
Contact-metamorphic	60.4	0.17	0.66	0.37	0.17	5.50
Bog ores	46.1	0.28	2.76	0.06	2.13	11.47

For one of the graphs, the average of the Venezuelan and Brazilian ores has been used, as follows: 68.8 per cent Fe; 0.02 per cent P; 0.35 per cent Al_2O_3; 0.02 per cent S; 0.17 per cent Mn; 0.40 per cent Si.

In Fig. 14, the analysis of the Venezuelan ores has been plotted with 20 others. In this diagram, logarithmic scale has been used in plotting the percentage of composition, because with such scale it is possible to notice variations of amount in substances which occur in very small quantity, such as phosphorus and sulfur. Furthermore, with logarithmic scale, besides the actual amounts of the components their proportions to one another are also given, represented by the slope of the line joining

[11] B. L. Miller and J. T. Singewald, Jr.: Mineral Deposits of South America, 536. 1919.

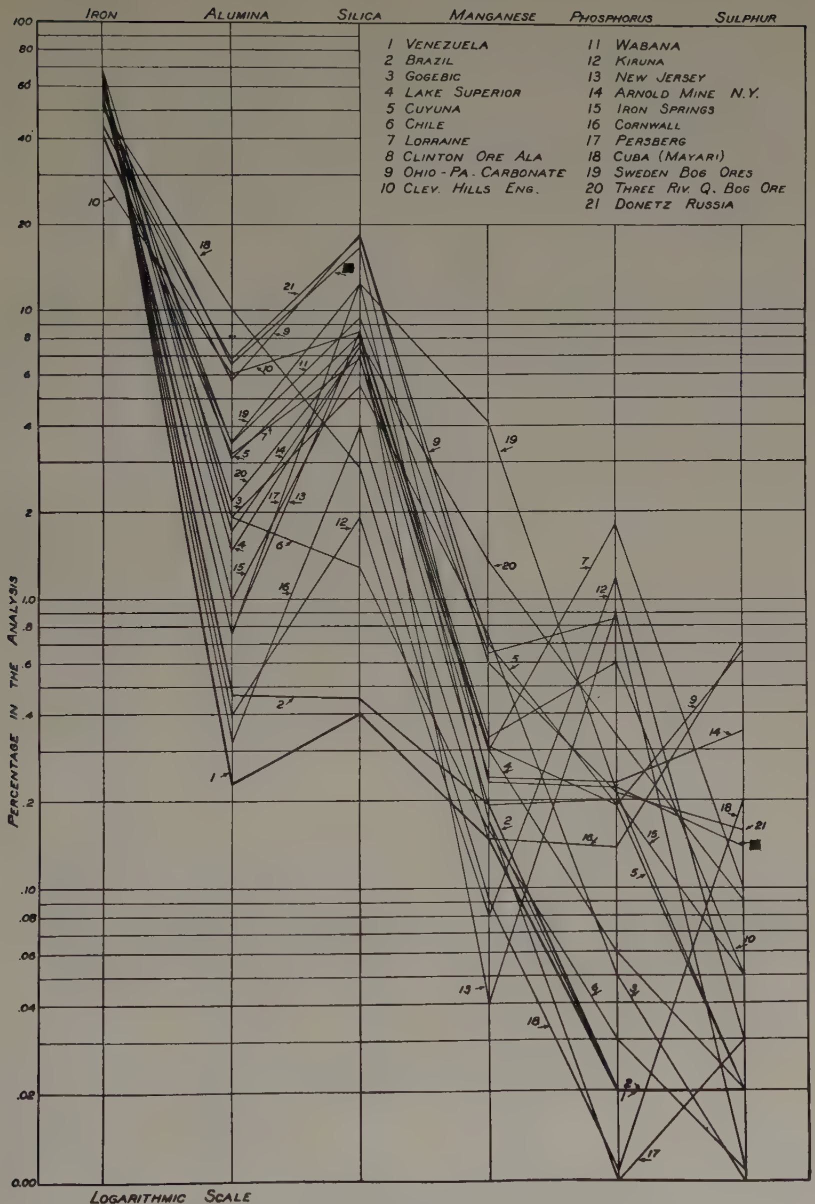

FIG. 14.—GRAPH COMPARING THE COMPOSITIONS OF VENEZUELAN AND OTHER IRON ORES.

them. Such being the case, it is also possible to notice whether there is any tendency for varying components to maintain a constant ratio with each other.

From this graph the following relations may be observed:

1. That the grade of the Venezuelan ores is practically unequaled, both in high percentage of Fe and in small percentage of impurities.

2. That the Brazilian ores are the most nearly similar ones, as shown by the proximity of the graphs.

3. That the Venezuelan and Brazilian ores are in a class by themselves, being different from the other ores in: (*a*) containing less than 1 per cent silica; and (*b*) not participating in the constant silica-manganese ratio as is shown by the parallelism of most of the lines joining those components. Other exceptions to this tendency are Gogebic, Chilean, and bog ores.

4. That the only ores lower in phosphorus are Persberg and Mayari; those lower in sulfur being Gogebic, Chilean, and New Jersey magnetite. Some New Jersey magnetite is higher in sulfur.

Fig. 15 has been plotted by using the average result of the analyses of the ores which have been classified according to genetic groups. In this graph we observe (*a*) again that the Venezuelan-Brazilian ores seem to be in a class by themselves and (*b*) that the same variation in the silica-manganese ratio takes place, Gogebic and bog ores being also different from the average.

The fact that the Gogebic ores show a tendency to approach the Venezuelan ores in composition is very interesting, inasmuch as geological conditions have certain similarities, there being dikes of basic rocks which cut the iron formations in the Gogebic, which may have had certain importance other than structural in the mineralization, as is shown among other things by the difference of the chemical analysis with the other Lake Superior ores. The Gogebic ores are the only ones lower than the Venezuelan and Brazilian ores in sulfur.

Ratio of Silica to Manganese

In the work of compiling and plotting chemical analyses of many iron ores, a curious relationship has appeared: the tendency shown for a constant ratio of silica to manganese. As already mentioned, in graphs plotted on a logarithmic scale, the slope of the lines joining two components indicates the ratio of change, so that if this ratio is the same for different analyses, the lines will be parallel.

The tendency for the silica-manganese lines to be parallel for different analyses was noticed after many graphs had been plotted, so there was no preconceived idea on the subject. After it was observed, a greater number of analyses were plotted, and Fig. 16 was obtained. With the exception of the lines labeled, the lines are almost all parallel. Not all the lines have been labeled, for lack of space.

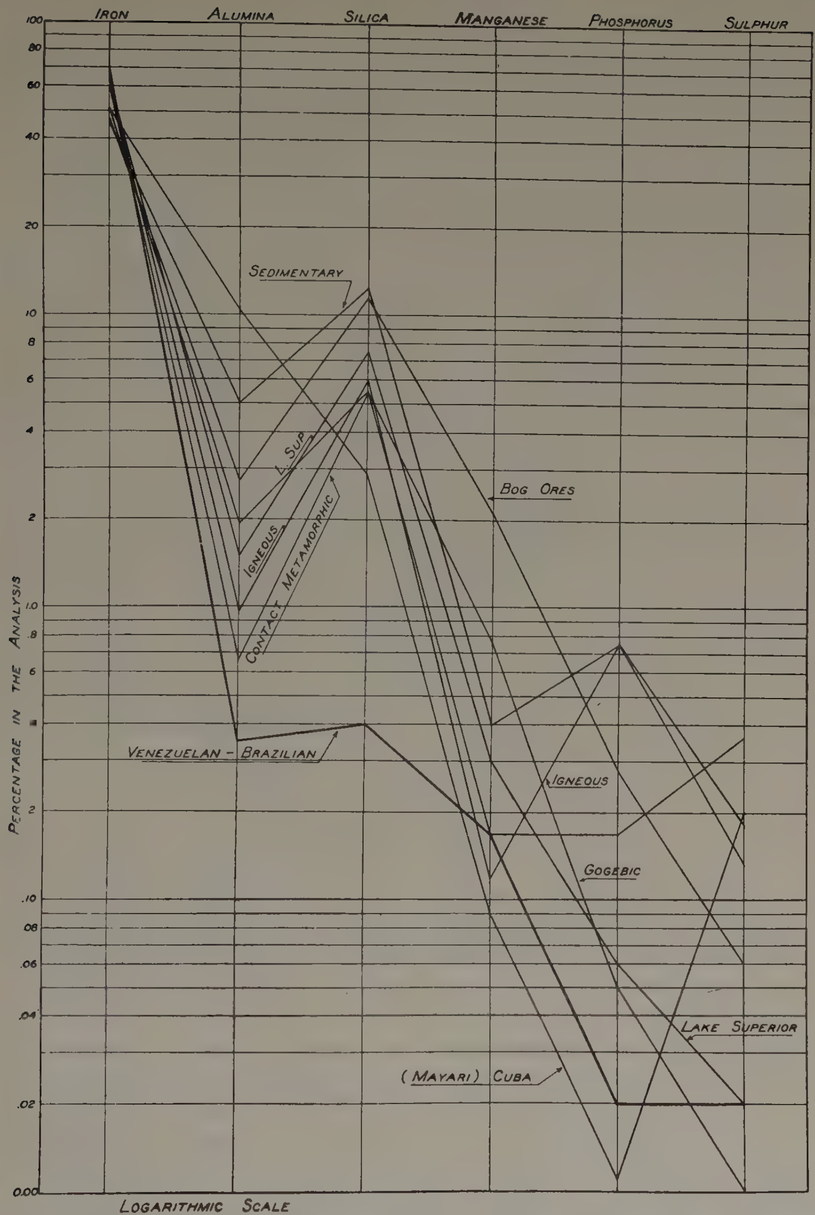

Fig. 15.—Graph comparing Venezuelan and Brazilian ores with different genetic groups of iron ores.

The line for sedimentary ore has been shifted by last-minute corrections.

There can be little doubt that the ratio of silica to manganese tends to be constant. On the average, there seems to be about 20 times as much silica as manganese. What this may mean is not known; but possibly it is due to some chemical association of the two components, which takes place under favorable conditions.

Comparison of Venezuelan and Brazilian Iron-ore Occurrences

In the preceding pages, it has been mentioned several times that there appears to be a great similarity between the geological features of the

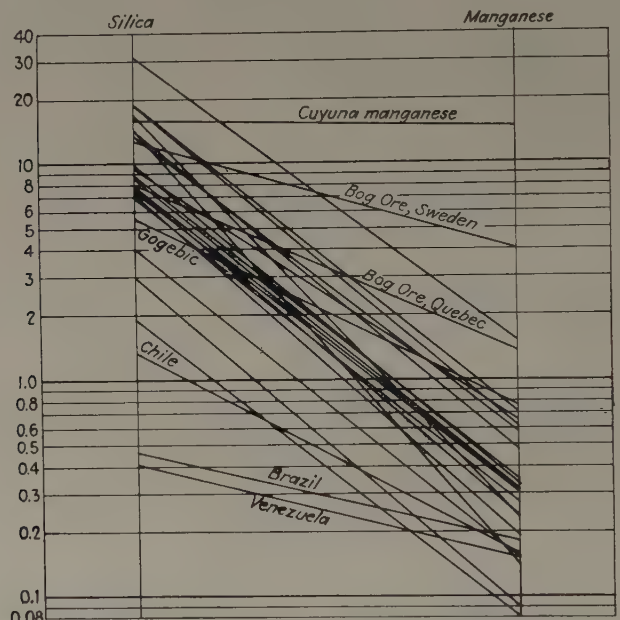

FIG. 16.—GRAPH SHOWING TENDENCY FOR A CONSTANT RATIO OF SILICA TO MANGANESE IN IRON ORES.

Venezuelan ores and those of Minas Geraes in Brazil. This similarity has been often remarked, and as a consequence it had been the hope of the present writer to apply the studies made on the Venezuelan ores to those of Brazil, and that if sufficient data were gathered to justify a theory for the origin of the ores different from those advanced for the Brazilian ores, the new theory might apply to both provinces.

However, although the similarity has been even increased in many points through the present investigation—for example, in the chemical analyses of the ores—some facts have come out that indicate differences in the geological features of the ores that point to different origin. The part played by intrusive rocks is the most important of these differences, as it has been found that in Venezuela intrusive rocks are possibly responsible

for the mineralization of the large orebodies while in Brazil no such cause has as yet been found.

The theory formulated by Harder, Chamberlin, and Leith[12] to explain the origin of the Brazilian ores is that the ores are of sedimentary origin, as are the itabirites. Quoting from the paper by Harder and Chamberlin, the banded iron quartzites "were laid down in a measure similar to limestone beds," and the rock is "a mixture of iron oxide and quartz laid down essentially as it occurs today. The principal change which it has undergone since its deposition is the dehydration which has converted the ferric hydroxide originally laid down into ferric oxide or hematite."

The rich orebodies are explained as being part of the sedimentary formation in which there was a smaller deposition of mechanical sediment such as quartz sand. "In the Brazilian iron fields . . . the itabirites and the iron being the original rocks."

Iron-precipitating bacteria are considered as a possible cause of the precipitation of the iron from solution.

In Venezuela, such a theory can well apply to the itabirite but not to the large orebodies, which have decidedly igneous affiliations. It seems incredible, however, that there would be such a profound difference of origin in ores with so many identical features. All that can be done is to await further data, and it is possible that reconciling facts will be found.[13]

In the meantime to quote from the article by Leith and Harder (p. 672): "It seemed to us that the sedimentary series is probably intruded by certain granites as well as underlain by them."

Comparison of Ores and Itabirites

A few samples of ores and itabirites from Brazil have been studied. In general it may be said that the most important difference is one of metamorphism, the Venezuelan rocks being more altered.

In the Brazilian itabirite studied, the iron oxide is mainly specular hematite, while in the Venezuelan itabirite it is generally magnetite; otherwise the rocks are identical, especially the structure of the quartz, which does not show growth lines, as is usual in quartzites.

In the ores again, hematite appears more abundant in the Brazilian ore, but magnetite is still present. The ores studied varied from exceedingly fine-grained massive specularite ore to ore made up of coarse blades

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[12] E. C. Harder: The "Itabirite" Iron Ore of Brazil. *Econ. Geol.* (1914) **9,** 101–111.

E. C. Harder and R. T. Chamberlin: Geology of Central Minas Geraes, Brazil. *Jnl. Geol.* (1915) **23,** 341–378, 385–424.

C. K. Leith and E. C. Harder: Hematite Ores of Brazil and a Comparison with Ores of Lake Superior. *Econ. Geol.* (1911) **6,** 670–686.

[13] A recent publication by B. H. Sanders [*Bull.* 346, Inst. Min. and Met. (July, 1933)] describes close areal and presumably genetic relations of rich iron ores with basic intrusives at Itabira, Brazil.

of specularite, as much as one centimeter in length. These radiate in what may originally have been vugs.

Comparison of General Geology

As has been mentioned before, the general geology of the formations in which the ores are found is very similar in Brazil and in Venezuela. They both occupy the same place in the geological section, being directly above the Archean complex, and they both occupy the same relation to the Brazilian Archean shield, being in both cases on the border, possibly as ancient coast lines.

However, in Brazil, shales and limestones are associated with the Itabira iron formation, while in Venezuela nothing but quartzite has been found; if other rocks existed they have been removed by erosion.

Comparison with Lake Superior

The geological differences from the Lake Superior ores may have become apparent in this discussion. The most important difference is the absence of chert or jasper in Venezuela,[14] and in Brazil.

The iron formations of Lake Superior, according to Leith, are "mainly of chert, or quartz, and ferric oxide segregated in bands or sheets, or irregularly mingled. Where in bands with the quartz layers colored red and the rocks highly crystalline it is called jasper, where less clearly crystallized and either in bands or irregularly intermixed the rock is known as ferruginous chert."[15]

The Lake Superior ores are the "product of enrichment of chemically deposited sediments, such as siderite and hydrated iron silicates, for the most part interbedded with normal clastic sediments, such as slate and quartzite."[16]

The iron formations in Venezuela and in Brazil do not contain red jaspers or chert, the quartz and the iron being segregated to form separate minerals.

Other Similar Ores

Iron ores associated with banded siliceous rocks are common throughout the world, and have originated in many different ways. Sydvaranger in Norway,[17] Krivoi Rog, in Russia, are among these ores.

In South Africa, the ores in the Crocodile River area[18] show much similarity to the Venezuelan ores, but again they are associated with chert.

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[14] One piece of jasper found by Burchard. Written communication.

[15] Quoted by Lindgren: Mineral Deposits, 496. 1928.

[16] W. Lindgren: *Op. cit.*, 405.

[17] W. Lindgren: *Op. cit.*, 913.

[18] P. A. Wagner: Crocodile River Iron Deposits. Geol. Survey South Africa *Mem.* 17 (1921).

DISCUSSION

(*Alan M. Bateman presiding*)

J. W. GRUNER,* Minneapolis, Minn. (written discussion).—The iron formation and iron ores of the Sierra de Imataca, so well described by Dr. Zuloaga, offer what almost amounts to proof that large iron orebodies form from sedimentary formations under the influence of heat given off by basic intrusives. Whether the solutions that remove the silica and bring in additional iron oxides come also from the magma or are circulating ground water heated by it cannot be decided at present. Very interesting is the serpentinization and decomposition in general of the basic intrusives at the contact with the ores; also the fact that, according to W. L. Cumings[19], martite octahedrons were obtained from the crushed serpentine by panning. This occurrence is strikingly similar to that in basic dikes at ore contacts on the Marquette Range. Since the origin of the Minas Geraes ores is always compared with that of the Pao district and the Lake Superior region, it might be mentioned that martite occurs in an exactly similar way in the decomposed dikes in the Brazilian ores. Sanders mentions these numerous dikes, which cannot be recognized at the surface. That they had something to do with the ore genesis is probable since tourmaline crystals are found in the dikes as well as in the hard hematite ores[20].

Dr. Zuloaga thinks that the iron formation proper is quartzite of clastic origin as far as its quartz is concerned, but he also emphasizes the fact that "the quartz is quite clear, being rarely strained; no growth lines are shown and the grains are never rounded; they interlock like those of granite. This may be due to recrystallization." I would say this must be due to recrystallization, since the grains become larger as the intrusives are approached. In the ancient iron formations that originally were ferruginous cherts, it is common to find large areas now "sugary quartzite" with little indication of chemical precipitation. It is questionable whether the true nature of such portions would have been recognized if it had not been for the conspicuous banding of the quartz due to the presence of amphiboles and other "impurities" as, for example, in the Lake Superior region. After all, the end products of metamorphism are chiefly a matter of degree.

Dr. Zuloaga's description of the iron ores proper could have been even more valuable if he had been a little clearer on the origin of the iron oxides. He mentions a number of different varieties of hematite from crystals of specularite 1½ cm. in diameter to very massive compact hematite, and also goethite in drill cores but not on the surface. And then he states, "Both the hematite and the goethite appear supergene, inasmuch as they are related to fractures," meaning fractures seen under the microscope. It is not quite clear why solutions could not rise as well as descend along such fractures. Incidentally, the samples of Pao ore in my possession are such coarse-grained and massive hematite (with very little magnetite) that it seems almost impossible that they are supergene.

Dr. Zuloaga mentions a rather surprising constancy of the ratio of silica to manganese. I cannot see this relationship in his analyses in Table 3. A ratio of between 15 and 25 to 1 is shown by only 7 of 23 analyses. The others vary between 2.5 and 200 of SiO_2 to 1 of Mn. It is common knowledge that in the Lake Superior region, for example, the manganese minerals are usually rather spotty in their distribution.

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[19] W. L. Cumings: Discussion. *Trans.* A.I.M.E. (1931) **96,** 374.

[20] B. H. Sanders: Iron Ores at Itabira, Brazil. Inst. Min. and Met. *Bull.* 346 (1933) 5, 11.

Only when very large cargoes are averaged is it possible to say that the ratio of $Mn:SiO_2$ is between 1:8 and 1:30.

Another point of analyses mentioned is that the Gogebic ores are the only ones lower in sulfur than the Venezuelan and Brazilian ores. The analysis of sulfur is rarely made on cargo shipments unless a complaint is received from furnaces for unusually high sulfur content. Therefore the figures quoted are not representative.

W. R. Cummings,* Bethlehem, Pa.—The question of the origin of the Pao ores is admittedly one that gives rise to interesting discussions. I believe that whatever mode of origin is admitted, it must also cover the large deposits in Brazil, as the two occurrences seem practically identical. The Brazilian deposits, I believe, are generally regarded as purely sedimentary. There are puzzling features at Pao that hint at igneous activity having had some effect and one of the geologists employed on the exploration was jokingly called "sedimentary" one week and "igneous" the next.

Most, if not all, iron ores of undoubted igneous origin or even those affected by igneous activity show small amounts of copper, vanadium, titanium and other elements. The magnetite-hematite ores of California, Mexico, Chile and Cuba contain varying amounts of such elements but at Pao these elements are absent. The sulfur is low and does not tend to increase in depth, as it invariably does in ores of igneous origin.

A peculiarity of the low-grade iron formation, or itabirite, as disclosed by drilling, was its lack of consolidation at depth. In many cases the drill men had great difficulty in pulling their rods when drilling in the itabirite. It acted much like quicksand and seemed to flow into the hole above the bit.

F. H. Kihlstedt,† New York, N.Y. (written discussion).—Dr. Zuloaga's paper and the discussion following it show that numerous phases of the genesis of iron ores remain unexplained, even as to what geological forces have been active in their formation. In Sweden, with its great iron ore resources, very complicated conditions are sometimes encountered in mines where bodies of entirely different type of ore are found close together. In several places there occurs very high-grade ore in mines that otherwise contain bodies of average or low grade. Although no generally applicable explanation is possible because of the varying geological conditions, one instance may be of interest in this connection; namely, the high-grade ore in the Bispbergs mine in Central Sweden. G. T. Lindroth has given a short description of the mine in *Geologiska Foreningens Forhandlingar*, Stockholm, 1930.

Three types of ore occur in the mine: quartz-banded hematite ore, generally considered to be a chemical sediment; talc ore of similar origin but with more Ca and Mg; and very rich hematite ore with some magnetite as an alteration product of the hematite. The latter ore is famous for its purity, even as iron ores go in Sweden. In the past about one million tons have been mined, with some ore remaining.

The quartz-banded hematite ores consist of alternating layers of hematite and quartz. The thicknesses of the layers vary a great deal, indicating rapid changes of the conditions during the sedimentation. Lindroth observed that when following the strike of the quartz-banded hematite ore towards the rich ore the quartz layers slowly thinned out and disappeared, leaving a very high-grade ore of the same composition and texture as the hematite layers in the former type of ore. The high-grade ore should thus in this case be considered as an abnormal development of a hematite layer, and therefore a primary feature, caused by a sudden increase of the iron supplied to the water, which presumably carried most of the iron from the volcanic

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* Geologist, Bethlehem Steel Co.

† Mining Engineer and Geologist.

activity, which also formed the surrounding tuffaceous sediments. Three of Lindroth's analyses are as follows:

	Quartz-banded Hematite	Hematite Layer	High-grade Ore
Fe	50.6	67.45	68.6
MnO	0.16	0.15	0.16
MgO	1.15	0.39	0.86
CaO	0.70	1.00	0.37
Al_2O_3	1.30	0.60	0.25
SiO_2	26.43	2.40	4.22
P	0.010	0.008	0.006
S	0.007	0.003	0.002

W. J. Millard, El Paso, Tex. (written discussion).—Several professional trips into southeastern Venezuela have resulted in the following interpretation of the general geology:

Name	Composition	Where Found	Thickness, Ft.	Age
Alluvials	Gravels and sandy clays	Flood plains and creek deposits	3–40	Recent
Llanos formation	Ferruginous sandstones and conglomerates—sometimes sandy clays underneath the above	Capping hills	4–100	Quaternary
Intrusives (1)	Gabbros			
Kaiteurian series	Quartz sandstone and conglomerates	Mounts Roiraima and Duida	3000	Triassic or Paleozoic
Intrusives (2)	Diorite, pyroxenite, granite and rhyolite			Paleozoic
El Callao series	Metamorphosed tuffs and appear as sericitic and chloritic schists	Gold-mining regions	0–3000?	Early Paleozoic or pre-Cambrian
Archean	Granite gneiss	Basement rock		Pre-Cambrian

Alluvials.—These often contain placer gold. In the Cuyuni River Basin from 12 to 18 in. of clayey gravel rests on a gray clay bedrock. The clay bedrock is either a false bedrock or decomposed sericitic schist. Above the gravel is from 3 to 40 ft. of gray sandy clay.

Llanos Formation.—Low mesalike hills are seen with ferruginous conglomerate caps between Ciudad, Bolivar and Guasipati. In the area near the headwaters of Chicanan similar caps exist. North of the Orinoco may be found many outcrops of this formation extending to the foothills of the coast range.

Intrusives (1).—In the vicinity of Mt. Roiraima, at the junction of the three countries, Brazil, British Guina and Venezuela, have been found dikes of basis rock cutting the Kaiteurian series. Diamond placers in British Guiana seem to be found invariably where this condition exists. Whether the basic dikes have been responsible for the diamonds is unknown. J. C. Branner has noted only one small basic dike in the diamondiferous quartzites of the State of Bahia in Brazil.

Kaiteurian Series.—Outcrops of these sandstones and conglomerates are found in the headwaters of the Cuyuni and Chicanan rivers. The best exposures are in a precipitous lot of mountains which extend spasmodically from Mt. Roiraima at the east of Mt. Duida on the west. Perpendicular slopes are common.

The color of the beds is often pinkish white and the pebbles of quartz in the conglomerates are well rounded. Shales are interstratified in places. In some localities intense folding and faulting has taken place. It is said that all drainage leading off these sandstones contains diamond placers. One instance is known of the occurrence of realgar or mercury ore.

The age is problematical. Branner has marked dubiously areas in the State of Amazonas in northern Brazil as containing Cretaceous sandstone and conglomerates. On page 230 in "Outline of the Geology of Brazil" he states, "In State of Amazonas Archean and Paleozoic are cut by dikes of eruptive rocks, but nowhere in the Amazonas region are the dikes known to part through Cretaceous and Tertiary." There is no doubt that his map had the Kaiteurian colored at questionable Cretaceous. Yet in British Guiana this formation is cut by basic dikes. Since there are areas of undoubted Cretaceous and Tertiary rocks in Brazil, it is believed the Kaiteurian is of an earlier age. In the Chicanan River near Chivao the Kaiteurian rests unconformably on the schists.

Intrusives (2).—Igneous intrusives of granite, rhyolite and pyroxenite are found in granite gneiss. Those of granite are perhaps the most numerous. Intrusives of diorite and pyroxenite have also been observed in the sericitic schists or metamorphosed tuffs. One slide of diorite indicated some movement after its intrusion and gave to it a slightly schistose appearance. Whether these intrusives were responsible for the mineralization of the schists by injecting quartz to form veins, lenses and silicified schist is not yet known. Slides of vein material indicated some mineralization after the veins had been formed. There was also replacement and movement in some veins.

El Callao Series.—Numerous specimens of schist taken at different localities in the mining districts under the microscope appear as metamorphosed volcanic ash. Some specimens of rock, which looked like blue limestone and brown sandstone, proved also to be metamorphosed tuffs. These later were interstratified with the schist. The schists are of great economic importance because all gold-bearing veins appear to be confined to them. They have been described by other geologists and engineers as sericitic and chloritic schists.

It is thought that in either pre-Cambrian or early Paleozoic time a great thickness of volcanic ash was laid down over the Guiana highland. Intense folding and pressure reduced the granite basement to granite gneiss and the volcanic ash to schists. The regional strike of both is the same. The intrusion of quartz into fissures, old bedding planes, and shear zones, as well as the development of lenticular bodies of quartz, may have taken place during the time of disturbance.

At present the schists exist more or less in belts as wide as 30 miles having a slightly north of east and south of west trend. It is believed that these belts represent uneroded synclinoriums as contrasted to eroded anticlinoriums to account for the generous areas of granite gneiss now exposed.

If sandstones existed in the Imataca area at this time there may have been a forming of ferruginous quartzites. However, it has always appeared to the writer in the past that the iron ore deposits near the Orinoco were of igneous origin rather than metamorphic. The Pao deposits were presumed to be the injection of magmatic solutions and filling of a fissure or line of weakness in the granite gneiss accompanied by stoping and eating away the walls, so as to give the deposits its ganglionic appearance. The deposit extends with a fixed strike and dip for a distance of one or two

kilometers, swelling out at one place to a width of 800 ft. Abundant silica in the vicinity of the Piacoa deposits can be explained as another phase of magmatic differentiation.

Archean Granite gneiss is by far the most common rock exposed. Hornblende schist, pyroxenite and fresh granite are common. The origin of the Archean is not as yet unraveled.

Barite Deposits in North Carolina

By Jasper L. Stuckey* and Harry T. Davis,† Members A.I.M.E.

(New York Meeting, February, 1933)

The object of this paper is to record and interpret field and laboratory observations made by the writers during five years of study of the barite deposits of North Carolina.

Deposits of barite are known to occur in three localities in North Carolina (Fig. 1) two of which—the Hot Springs and Kings Mountain—contain material of economic value. The Hot Springs area begins near Bluff, some 6 miles south of Hot Springs, and continues northeast by Stackhouse; a total length of 7 miles. The Kings Mountain deposits lie along a belt that extends from the north end of Crowders Mountain in a southwestward direction, along the east side of this and Kings Mountain, to Kings Creek, South Carolina. The third locality is 3½ miles southeast of Hillsboro, Orange County, a short distance west of the highway leading from Hillsboro to Chapel Hill.

It is not known when barite was first discovered in North Carolina, but production from the Hot Springs area began some 50 years ago. The state has never produced large quantities of barite—usually there have been less than three producers—and definite figures are not available, but reasonably reliable estimates indicate a total production of 300,000 tons. From 1901 through 1920 barite mining was on a seemingly prosperous basis and a large tonnage was shipped from the Hot Springs and Kings Mountain areas. With the depression of 1920 the industry began to decline and production practically ceased in 1926.

Geology of the Barite Areas

In the Hot Springs area barite is found in the Max Patch granite of Archean age and the Snowbird formation of Cambrian age. The Max Patch granite is of two varieties, one gray to whitish and the other red. The gray granite is coarse, at times porphyritic, and composed of quartz, orthoclase and plagioclase feldspar, with a little biotite and muscovite. The red granite is also coarse and differs from the other only in having conspicuous pink and red feldspar. Both varieties have been much metamorphosed and weathered in places, so that they contain secondary

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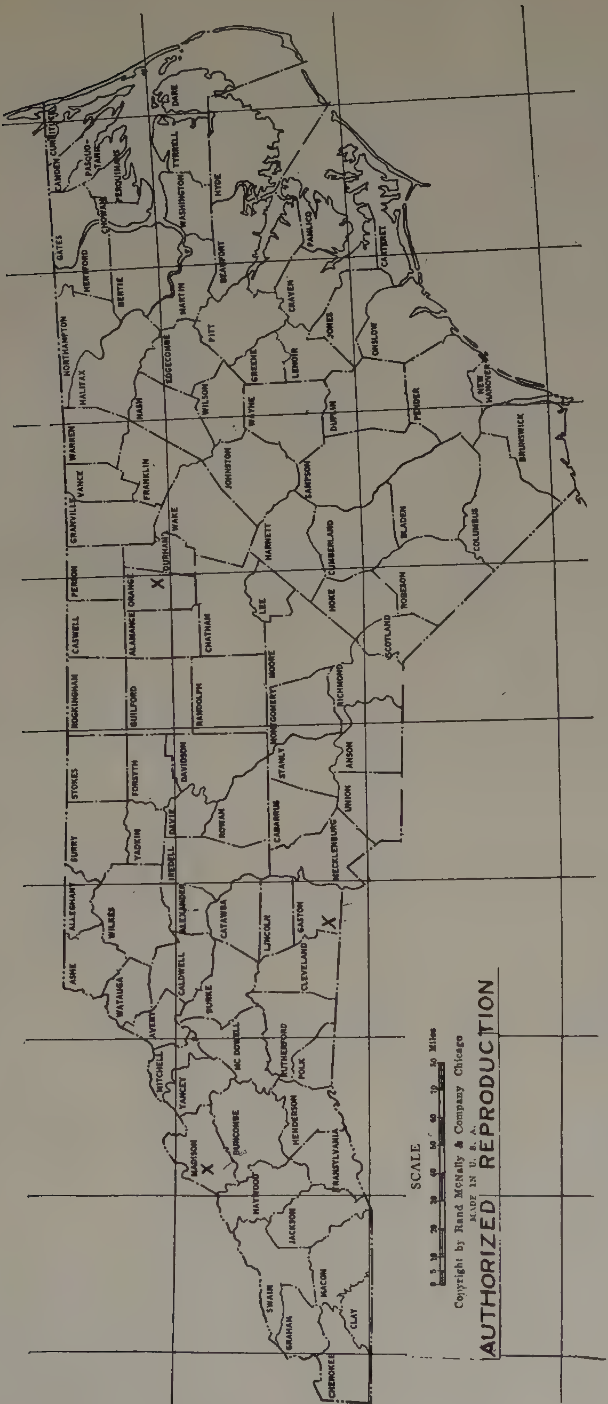

FIG. 1.—OUTLINE MAP OF NORTH CAROLINA SHOWING LOCATION OF THREE AREAS WHERE BARITE IS KNOWN TO OCCUR.

minerals, the chief of which is epidote. Barite occurs in both the red and the white granite.

The Snowbird formation is made up of fine and coarse quartzites, with which are interstratified beds of conglomerate, arkose and small amounts of gray and black slate. Feldspar is abundant in some of the quartzites, while others consist almost entirely of quartz. The slates are fine grained and argillaceous, at times micaceous. Barite is found in this formation chiefly in the feldspathic quartzites, but at some of the old mines gray slate was extracted with the barite.

In the Kings Mountain area, barite is found in the Battleground schist of Algonkian age and to a limited extent in the Bessemer granite of Archean age. The latter is a medium to fine-grained rock, at times porphyritic, which has been metamorphosed in most places to a white and gray quartz-sericite schist. In the less altered portions it contains quartz, orthoclase, oligoclase, muscovite, biotite, and a little magnetite and zircon.

The Battleground schist is a sericite schist of white, bluish gray and mottled colors. Sandy quartzitic varieties of the schist occur, with some of which are conglomeratic beds. The rock is of composite origin, and originally consisted of volcanic breccia, tuff, ash and mud, associated with flows of rhyolite and andesite.

The barite near Hillsboro is found in highly metamorphosed volcanic rocks of Algonkian age. These volcanics consist of both fragmental and flow materials. The barite occurs in an acid tuff of medium texture. No flow materials were seen in place at the openings, although small amounts of altered andesite were seen on the dumps and a few hundred feet from the opening.

Barite Deposits

Hill[1] divides barite deposits according to occurrence, into three classes, as follows:

1. Those that occur as a gangue mineral in metalliferous deposits.
2. Veins in sandstones, limestones or crystalline rocks.
3. Residual deposits derived from the weathering of barium-bearing rocks; the typical residual deposits being in a clay that has been derived from the weathering of magnesian limestone (dolomite) of Cambrian or Ordovician age.

The North Carolina deposits belong in class 2. They are found in irregular veins and lenses in crystalline rocks.

Hot Springs Area.—In the Hot Springs area the barite occurs in massive granites of Archean age and to some extent in the feldspathic quartzites of Cambrian age. It is generally found near the contact of

[1] J. M. Hill: Barytes and Strontium. *Mineral Resources of the United States*, U. S. Geol. Survey (1915) Pt. 2, 161–187.

the two formations. The granites and quartzites have been badly crushed and broken. At least two major thrust faults which trend north-northeast have been located in this area. While the barite deposits are not found directly in the zone of faulting their close proximity to this zone indicates that the mineral-forming solutions found this a favorable path of ingress.

The veins are irregular in shape and size, averaging from a few inches to 6 ft. (maximum 18 ft.) wide and conforming in general with the strike and dip of the rocks. The general position of the veins and the occurrence of the barite in large crystals and crystalline masses, which do not show the great deformation of the minerals in the enclosing rocks, indicate conclusively that the barite was formed after the main period of faulting and deformation.

Near Bluff, 6 miles south of Hot Springs, on the southern end of the barite zone, one of the most important deposits in the area occurs in feldspathic quartzite. Here the barite veins seem to be controlled by the fault zone, since much of the material on the dumps shows that the vein has been formed in part in a brecciated quartzite. The barite occurs in crystals and large crystalline masses and varies from white to gray or yellow in color. Associated black fluorite is abundant. The barite and fluorite are often banded, with small amounts of sulfides (Fig. 2).

Beginning about one mile north of Stackhouse and continuing for some 2 miles to the northeast, extensive mining has been done on the Stackhouse, Mashburn, Betts and Gahagan properties. The barite deposits on the first three properties are much alike and lie in gray granite near fault zones.

At the Stackhouse mine—said to be 500 ft. deep—much black slate is seen on the dump. No barite, however, has been seen within the slate. Barite occurs as well developed crystal grains and as crystalline masses of large size. Its color is white to gray and it is often banded after the manner of vein filling. Violet blue to colorless fluorite is abundant as irregular masses and grains. On the mine dumps masses of silicified granite contain pyrite, barite and fluorite.

The Gahagan mine is near the fault zone in red granite. Where the barite has been removed the granite walls are decidedly red and the feldspars noticeably unweathered. The vein, which is 3 to 6 ft. wide, is composed of barite and fluorite—characteristically banded. On the dump large masses of silicified granite contain pyrite, white to yellow barite and violet blue to colorless fluorite.

Kings Mountain Area.—A number of deposits of barite have been prospected or worked in the Kings Mountain area, typical of which is the Lawson mine about one mile southeast of the southern end of Crowders Mountain. The rock in which the barite occurs is a fine-grained, white

siliceous sericite schist (Algonkian). The schist strikes N.10°–20° E. and dips steeply to the northwest. Bodies of Bessemer granite (Late Archean) are found near the barite and a cyanite-bearing quartzite is found a short distance west of the openings. Two parallel veins occur on the

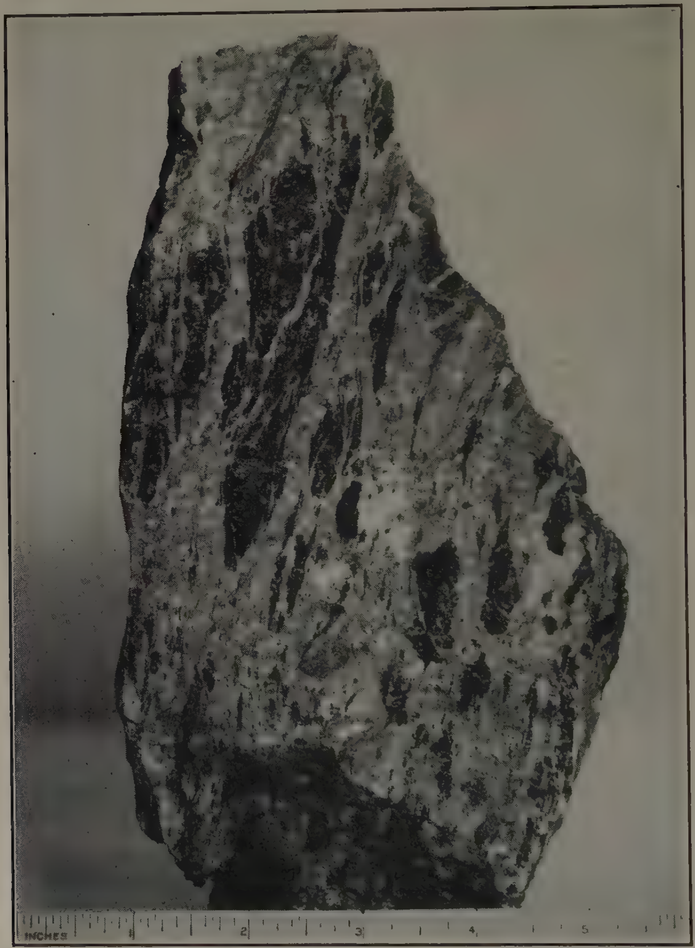

FIG. 2.—HAND SPECIMEN SHOWING FLUORITE (BLACK) BANDED WITH BARITE.

property, which vary in width from a few inches to 6 ft. (in one case 12 ft.) and conform in general with the strike and dip of the schist.

The barite in the veins is massive granular, with cleavage faces of a maximum of 2 in., and frequently contains quartz in crystalline masses up to ½ in. in diameter. The best barite is snow white, but light pink and yellow colors are present.

Hillsboro Area.—The barite near Hillsboro is found in a sheared volcanic tuff of Algonkian age. This rock has a cleavage which strikes

N.20°E. and dips steeply to the northwest. The small barite veins or lenses apparently conform with the cleavage. The only minerals observed are barite and quartz. The tuff has been much silicified and contains vein quartz containing an abundance of crystals up to one inch or more in length. The barite has been deposited on the quartz crystals and masses. Beautiful snow white crystals and cleavage faces of 3 in. are common.

Mineralogy and Petrography

The minerals observed in the barite veins and lenses include barite, fluorite, quartz, sericite, calcite, pyrite, galena, chalcopyrite and sphalerite. Barite varies in color from snow white and gray to yellow and in structure from fine-grained masses to crystals and cleavage blocks up to 3 in. Fluorite varies in color from black through violet blue to gray and colorless. It is found only in the Hot Springs area, where it occurs as irregular lenses and bands alternating with barite (Fig. 2). Quartz is present in all the deposits as crystals one inch or more in size. Sericite in small amounts occurs as flakes in the siliceous barite material found both in the quartzite and granite in the Hot Springs area. Calcite in small amounts was observed in one or two specimens from near Stackhouse and in one specimen from Crowders Mountain.

Pyrite, galena and chalcopyrite were observed in varying amounts in the impure siliceous barite and to a limited extent in good barite from the Hot Springs and Kings Mountain areas. Sphalerite was observed in small masses associated with galena in the impure barite from Crowders Mountain. Iron oxide stains are common where the veins have been weathered.

A careful study of thin sections cut from various portions of the different veins shows definite relationship among the minerals present. A varying amount of silicification has taken place along the wall rocks, regardless of their original nature. In some places, as at Crowders Mountain and near Hillsboro, the development of barite or barite and sulfides followed that of the quartz. In the Hot Springs area small amounts of sericite were developed following or along with the quartz. Sericite was observed replacing the silicified wall rock of the veins in places, and in other places it was in cracks in quartz and unaltered feldspars. The sulfides, pyrite, galena, chalcopyrite and sphalerite seem to have developed most abundantly following silicification, as they are far more abundant in the impure material near the wall rocks. These sulfides are present in small grains and irregular fragments more or less banded with silica, barite and fluorite, where the latter is present. Following the sulfides, barite and fluorite seem to have been deposited as contemporaneous minerals, the fluorite later giving way to barite. Where either barite or fluorite came in contact with quartz, some replacement of that mineral resulted. In the banded veins barite and fluorite were deposited alter-

nately (Fig. 3) and replaced each other to a limited extent. In some of the granite specimens cracks in quartz and feldspar were observed partly filled with fluorite and partly filled with barite (Fig. 4). This order of deposition was probably progressive, since small amounts of quartz and the sulfides and fluorite are found in the best of the barite.

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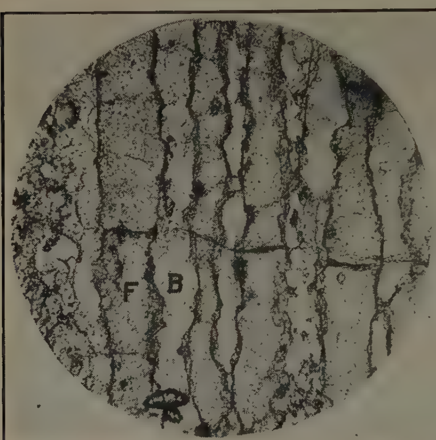

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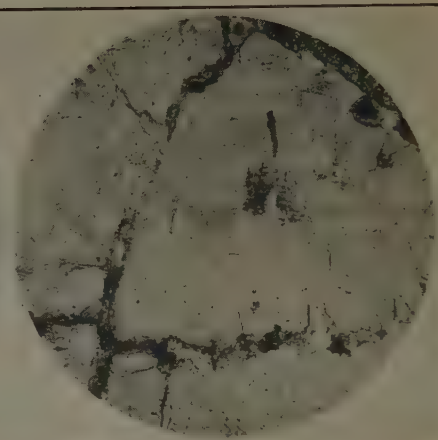

FIG. 3.—THIN SECTION SHOWING FLUORITE (F) BANDED WITH BARITE (B). ORDINARY LIGHT. × 50.

FIG. 4.—THIN SECTION SHOWING CRACKS IN ORTHOCLASE FELDSPAR PARTLY FILLED WITH FLUORITE (BLACK) AND PARTLY FILLED WITH BARITE (WHITE). CROSSED NICOLS. × 50.

There is also an apparent later generation of quartz and barite. In thin sections veinlets of quartz were observed cutting grains of barite and fluorite, and barite fills cracks in and around older minerals.

ORIGIN OF BARITE

The literature on barite is extensive and theories of origin are more or less in controversy. Where barite occurs as a gangue in metalliferous deposits, there seems to be agreement as to its magmatic origin. Likewise residual barite has doubtless been concentrated by weathering—whatever its original source.

Tarr[2] believed that the residual barite in Washington County, Missouri, came from veins in the bedrock; also, that the veins were formed by hot solutions of magmatic origin. Dake,[3] in a recent study of the same region, believes that the barite in the bedrock was concurrently deposited with the bedrock and as colloidal barite from sea water.

[2] W. A. Tarr: The Barite Deposits of Missouri. Univ. of Missouri *Studies* (1918) **111**, No. 1.

[3] C. L. Dake: The Geology of the Potosi and Edgehill Quadrangles. Missouri Bur. Geol. and Mines [2] (1930) **23**, 201–207.

Watson and Grasty[4] indicated that the barite in veins in sedimentary and crystalline rocks—in the southern Appalachians—was derived from the surrounding rocks by shallow circulation. Adams,[5] in his recent study of the barite deposits of Alabama, believed that the barite now found in veins and residual deposits was originally formed by magmatic emanations.

Origin of North Carolina Barite

The field and microscopic evidence gathered by the writers indicates that the barite veins in the igneous and metamorphic rocks were formed by magmatic solutions. This evidence may be summarized as follows:

1. The veins occur in granites, schists and schistose volcanics.
2. The wall rocks of all the veins have undergone silicification regardless of their original nature.
3. The adjacent wall rocks show no signs of weathering or leaching.
4. Sericite is present in the quartzite and granite wall rocks.
5. Pyrite, chalcopyrite, galena and sphalerite are present in all the veins.
6. Quartz crystals and masses are present in all the veins.
7. Fluorite banded with barite is present in the veins.

Sericite is classed as a hydrothermal mineral. Chalcopyrite and argentiferous galena are considered primary minerals. Genth[6] reports argentiferous galena in the Hot Springs area, and blowpipe tests on galena, with barite from Bluff, confirms this. Nitze[7] reports galena in the gold ores from the Kings Mountain area and shows by assays that these ores carry silver. Gold has been mined within a few hundred feet of the Hillsboro barite deposit. The quartz of the barite veins is of the same type as that occurring with the gold ores of the region. The fluorite banded with the barite shows contemporaneous and alternate deposition. Thin sections show that barite in part replaces fluorite,[8] and fluorite likewise replaces barite.

The mineral veins were formed after major deformations. The deposits are largely due to vein filling, which probably took place under intermediate or low temperatures. Magmatic solutions presuppose igneous activity. For such activity there was the development of

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[4] T. L. Watson and J. S. Grasty: Barite of the Appalachian States. *Trans.* A. I. M. E. (1915) **51,** 514–559.

[5] G. I. Adams: Hydrothermal Origin of the Barite in Alabama. *Econ. Geol.* (1931) **26,** 772–776.

[6] F. A. Genth: Minerals of North Carolina. Appendix C to W. C. Kerr's Report, Geol. Survey of North Carolina (1875).

[7] H. B. C. Nitze and G. B. Hanna: Gold Deposits of North Carolina. N. C. Geol. Survey *Bull.* 3 (1896) 146–148.

[8] B. M. Shaub has recently described replacement between alternate bands in a study of banded veins carried out in the Laboratory of Geology at Cornell University. Unpublished manuscript.

igneous rocks in the Appalachian Mountains and Piedmont Plateau during late Carboniferous time. In the Kings Mountain quadrangle the Whiteside and Yorkville granites of late Carboniferous age are exposed near the barite deposits. In the Hot Springs area—Asheville quadrangle —masses of fine-grained granite up to 100 ft. wide and 600 ft. long are abundant. Keith[9] classes these as late Carboniferous. In the adjoining Pisgah quadrangle Whiteside granite is abundant.

Mining and Reserves

In the Hot Springs belt of barite deposits the principal properties developed have been those known as Bluff, Stackhouse, Mashburn, Betts and Gahagan, reading in a northeast direction along the belt.

The topography of the region is mountainous and the openings that have been made are 500 to 800 ft. above the streams. With one exception (500 ft.) the operations extended to a depth of less than 300 ft. Shafts of this type with open pits and outcrops have shown the persistence of the veins on all the properties named above. The veins average 2 to 4 ft. in width, with variations up to 18 ft. in the deep shaft on the Stackhouse property. Discarded material on the mine dumps shows that some of the barite is badly intermixed with fluorite, quartz and sulfides, but by crude hand-picking a merchantable product of 94 per cent $BaSO_4$ was marketed. Thousands of tons of barite have been produced from the most promising parts of the veins by sporadic operations. A large reserve is present, however, which doubtless will justify development and profitable mining.

In the Kings Mountain area many shallow pits and shafts show sporadic development from the north end of Crowders Mountain to Kings Creek, South Carolina, a distance of 15 miles. Most of the pits and shafts show that the barite is persistent and that a large tonnage is available to inexpensive mining. The elevations are favorable and the shallow overburden can be removed by stripping for open-pit mining. Apparently a very good quality of barite has been produced and marketed with comparatively crude processing.

Most important in North Carolina are the Lawson and Craig properties. The Craig property shows two veins, varying from 2 to 6 ft., opened by shafts and shallow pits to 35 ft. in depth. The Lawson property is developed by numerous old shafts and pits from 30 to 100 ft. deep. Two veins, about 100 ft. apart, are exposed; they vary from 2 to 6 ft. (in one case 12 ft.) in width. During 1923–1924 this property was further developed to a depth of 200 ft., and a large tonnage was thus blocked out, which is reported as being held in reserve. Other properties in this area are potentially as important as the Lawson property.

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[9] A. Keith: Geological Atlas of the United States. Asheville Folio (1904) No 116, 2.

DISCUSSION

(*Albert O. Hayes presiding*)

W. A. Tarr,* Columbia, Mo. (written discussion).—I was very glad to learn that the authors have assigned a magmatic origin to the barite deposits of North Carolina. As they say, I have advocated a magmatic origin for the barite deposits for the state of Missouri. In a recent paper[10] I described a barite vein cutting the granite within about 25 miles of the major barite deposits of the state. The interesting thing about this vein is its similarity to some of the features found in the veins in North Carolina. Although the vein is small, the minerals are all very well developed. The first mineral deposited was pyrite, followed by fluorite, and lastly by barite and a second recurrence of pyrite that was essentially contemporaneous. There can be no doubt that this vein was of magmatic origin, as are those of North Carolina. The nearness of this vein to the important barite deposits some miles away is further evidence that those veins were of magmatic origin.

I am glad to see that the evidence that favors a magmatic origin for so many of our barite deposits is accumulating.

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* Department of Geology and Geography, University of Missouri.

[10] W. A. Tarr: A Barite Vein Cutting Granite of Southeastern Missouri. *Amer. Mineralogist* (1932) **17**, 443–448.

Some Strontium Deposits of Southeastern California and Western Arizona*

By Bernard N. Moore,† Member A.I.M.E.

(New York Meeting, February, 1935)

At present the demands of the United States for strontium are met by imports from Germany, England and Canada, which vary considerably in proportions of ore and finished salts, in tonnage and in value. Statistics for the period 1926–1932 are given in Table 1. Domestic deposits are known in many states, but the larger and purer ones are in the West, particularly in the desert region of southeastern California and western Arizona. These deposits are large enough to command interest, particularly in consideration of future cheap power at the Boulder Dam.

Table 1.—*Strontium Imported into the United States, 1926–1932*[a]

Year	Ore		Chemicals	
	Short Tons	Value	Pounds	Value
1926	2,200	$58,159	5,433,044	$115,436
1927	1,356	58,711	4,233,816	149,383
1928	759	31,157	3,380,464	136,561
1929	973	45,505	4,578,327	196,233
1930	220	10,459	2,153,788	104,807
1931	(260 lbs.)	123	1,742,714	83,564
1932	5	276	469,481	20,910

[a] *Mineral Industry* (1934) **42**, 61.

The deposits described in this paper were examined during an investigation of the mineral resources of the Boulder Dam region by the United States Geological Survey for the United States Bureau of Reclamation in the spring of 1934. Mr. D. F. Hewett, who had general charge of the investigation, Mr. W. T. Schaller and Mr. M. I. Goldman contributed many helpful suggestions. Mr. N. H. Harshman assisted efficiently during the field work.

Celestite Deposits

The celestite deposits described in this paper are of sedimentary origin and Tertiary age. They are widely scattered, as shown on Fig. 1,

* Published by permission of the Director of the U.S. Geological Survey. Manuscript received at the office of the Institute Nov. 28, 1934.

† Assistant Geologist, U.S. Geological Survey, Washington, D.C.

but are part of an extensive series of Tertiary basin deposits composed mainly of volcanic ash and detritus from areas of volcanic rocks. In them are interbedded large deposits of salt, boron minerals, magnesite, dolomite, limestone and celestite. The make-up of the Tertiary basin deposits varies from one basin to another; in some basins only one of these minerals is present, but in others several are present over large areas. Such elements as boron and strontium, in particular, are present in very small percentages in the soluble derivatives of rock weathering. The

FIG. 1.—INDEX MAP SHOWING LOCATION OF KNOWN STRONTIUM DEPOSITS IN SOUTHEASTERN CALIFORNIA AND WESTERN ARIZONA.

1. Avawatz Mountains.
2. Barstow.
3. Argos.
4. Fish Mountains.
5. Aguila
6. Gila Bend.

presence of large deposits of their minerals in a high degree of purity suggests that other processes were involved in their formation than the concentration of normal ground and surface water in enclosed basins.

Argos

Location.—The Argos celestite deposit lies in the dissected fan heads of the southern slope of the Cady Mountains in secs. 19 and 20, T.8N., R.7E., about three miles northwest of Argos station, in San Bernardino County, California. Seen from the highway or railroad, it appears as a series of white croppings above the dune sands that cover the fans. Although the deposit has been known for a long time and, to judge from the workings, has produced celestite rock, the only description has been a brief note by Mallery[1].

[1] W. Mallery: A Discovery of Celestite. *Min. & Sci. Pr.* (1916) **113**, 952.

General Features of District.—The Cady Mountains are a high, rugged range formed of a chaotic succession of brightly colored volcanic formations, including ash, lavas, and dike and stock rocks, which trend from west to N.60°W. Along the southern base of the range a coarse white tuff, part of the volcanic series, is exposed and is overlain by a shaly tuff that contains the celestite rock.

Celestite.—The celestite zone crops out for 4000 ft. along the center of the mountain front, as shown in Fig. 2, and is dislocated by obscure faults, which are indicated by the displacement of the outcrops. In the eastern part of the area the dips are about 20°S., but in the western part they average 50°S. The celestite occurs in beds as much as 5½ ft. thick

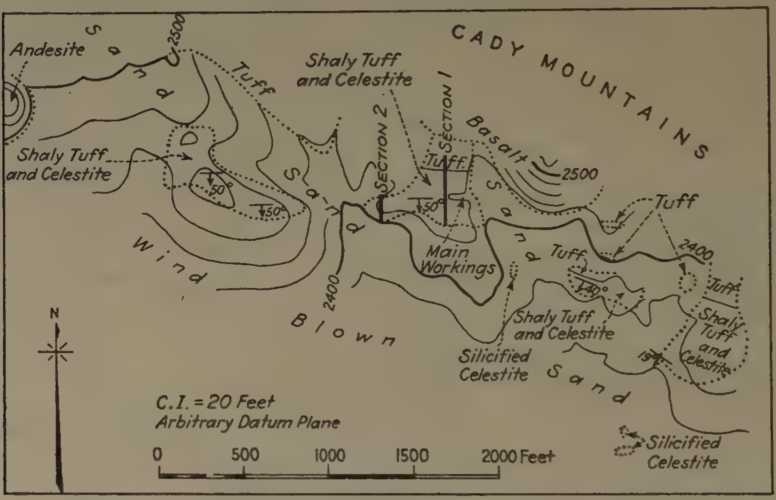

Fig. 2.—Sketch showing geologic relations of celestite croppings near Argos, San Bernardino County, California.

interbedded with shaly tuff and tuffaceous clay. It is mostly a finely crystalline rock of light buff and green tints, but some varieties are almost porcelaneous in texture and have a delicate pink tint. Microscopic examination shows that it all contains some chalcedony, which has replaced the celestite. In the eastern part of the district jasper and chalcedony have replaced large bodies of the celestite rock.

The mode of occurrence of the celestite is shown by the sections in Table 2. (See also Fig. 2.)

Table 2.—*Sections in Celestite Zone near Argos, in SE.¼ sec.* 19, *T.8N., R.7E., San Bernardino County, California*

Section 1 (Measured from South to North)

	Ft.	In.
Top of section hidden by dune sand.		
Interbedded fine-grained celestite rock and shaly tuff; celestite rock in beds as much as 4 in. thick forming ¼ to ⅓ total thickness....................................	61	8

TABLE 2.—(*Continued*)

	Ft.	In.
Massively bedded celestite rock, fine-grained, light olive-buff	2	
Interbedded celestite rock and shaly tuff; celestite rock in beds as much as 4 in. thick forming ¼ to ⅓ total thickness	37	5
Light olive-buff shaly tuff, stained in places by manganese oxides and bearing calcareous concretions containing notable concentrations of strontium as strontianite and of manganese. (For analyses see Table 8.)	11	
Interbedded shaly tuff and celestite (details below)	41	9

(Except where otherwise noted the celestite rock is a massive fine-grained material stained various olive-buff and green tints by slight amounts of admixed clayey material and contains in places stains, streaks and nodules of manganese oxides. The interbedded clayey and shaly tuffs are similar to other reworked tuffs.)

	Ft.	In.
Celestite rock with thin partings of shaly tuff	1	6
Shaly tuff		3
Celestite rock, locally silicified	1	10
Clayey tuff		3
Celestite rock, shaly at base (sample 6)		11
Clayey tuff		2
Thin-bedded celestite rock with clayey partings	1	
Clayey tuff		2
Shaly celestite		1
Clayey tuff		1
Celestite rock, massive		6
Clayey tuff		3
Celestite rock		1
Clayey tuff		6
Celestite rock; bottom of bed shaly; central part contains streaks of manganese oxides and has been considerably recrystallized; upper part nearly grainless and surface marked by cauliflowerlike rugosities		10
Clayey tuff		½
Celestite rock		1½
Clayey tuff		4
Celestite rock		2
Clayey tuff		2
Thin-bedded celestite rock and clayey tuff with many manganese nodules from pin-head to pea size; some gypsum veinlets		6
Massive celestite rock		6
Interbedded celestite rock and clayey tuff		9
Clayey tuff		3
Massive celestite rock		6
Thin-bedded celestite rock with green clayey partings		5

Table 2.—(*Continued*)

	Ft.	In.	Ft.	In.
Celestite rock; laminations marked by faint streaks of greenish clayey material along which manganese oxides have been deposited (sample 5)	3	5		
Thinly laminated celestite rock with thin clayey partings; manganese stains common (sample 4)	1	6		
Green ocherlike material	1	4		
Red ocher	2	10		
Green ocherous clay	4			
Thin-bedded celestite with thin partings of clayey tuff (sample 3)	1	8		
Green ocherous clay with celestite nodules	1	8		
Thin-bedded celestite rock and clayey tuffs, in part jasperized	1	8		
Thin-bedded celestite rock with parrings of shaly tuff; more than ¾ celestite rock	5	3		
Clayey tuff with celestite nodules, in part silicified and forming about ¾ of total material (sample 2)	1	9		
Celestite rock, massive, but with faint streaks of clay suggesting lamination in places (sample 1)	4	6		
	41	9		
Covered by alluvium			6	
Croppings of celestite rock			2	
Covered by alluvium			4	
Croppings of celestite rock			2	
Shaly tuffs with numerous red and yellow jasperized beds; details hidden by alluvium			41	
Shaly tuffs; details hidden by aluvium			93+	
			301	10+

Section 2 (Measured from South to North 500 Feet West of Section 1)

	Ft.	In.
Top of section hidden by dune sands.		
Massive celestite characterized by numerous cavities and stained brown from weathering (sample 9)	3	5
Covered by alluvium	13	
Massive sugary celestite rock showing evidence of some recrystallization and streaked pink. Along the weathered pink stripes, black manganese oxide occurs (sample 8)		6
Covered by alluvium	15	
Fine-grained massive celestite rock striped pink and light buff and silicified in many places in direction of the stripes (sample 7)	2	3
Covered by alluvium	8	6
Massive celestite rock rendered porous by weathering and marked by numerous red stripes. Manganese oxides		

TABLE 2.—(*Continued*)

	Ft.	In.
form streaks and tiny nodules, and there are many silicified spots in the rock (sample 6)	2	3
Covered by alluvium	3	2
Very fine-grained, almost porcelaneous light-pink celestite rock, containing at base streaks of large sand grains and small pebbles of volcanic rocks. Small masses of manganese oxides the size of a pinhead are common (sample 5)	8	4
Covered by alluvium	1	6
Massive fine-grained celestite rock streaked pink and spottily silicified (sample 4)	1	6
Covered by alluvium	12	6
Fine-grained light olive-green celestite rock showing recrystallization along veinlets (sample 3)	4	6
Thin-bedded celestite rock and shaly tuff	6	
Celestite rock, fine-grained, light olive-green, with a few clayey partings (sample 2)	3	
Celestite marked by thin laminations defined by thin streaks of clayey tuffs and colored pink along laminations (sample 1)	5	6
Green ocherous clay		3
Celestite rock, massive, fine-grained	1	
	81	8

As shown by the sections, the maximum thickness of the beds of celestite rock is 5½ ft. The thickest bed is the one from which sample 1 of section 1 and sample 1 of section 2 were taken and may be traced for about 500 ft. The outcrops of the beds of section 2 may be traced several hundred feet. In the main workings (Fig. 2) the beds detailed in section 1 above the red ocher are well exposed for study. The thicker beds finger out in places into thinner beds separated by the shaly tuff; in places, where beds end thin lenticular bodies appear along projections of their strike. A suggestion that similar variation occurs on the dip is furnished by the 5½-ft. bed, which in the shaft on the line of section 2 decreases to 2½ ft. in a distance of about 50 feet.

The bedding is well marked by the contacts of the celestite rock with the shaly tuffs. The contacts are distinct but are not sharp in the sense of forming surfaces of easy parting. The shaly tuff and celestite rock are firmly united by a very thin transition zone, even where the celestite beds are thinnest. At the base of the bed of very fine-grained celestite rock from which sample 5 of section 2 was taken, gravel and tuff particles parallel to the base are interbedded for a few inches. The upper part of the thicker beds is commonly warty, and in one place irregularities were noted that were similar to a cauliflower in shape and suggesting the forms observed in open-pan evaporation of salines. The upper part of another bed showed numerous clay-filled cracks but was not sufficiently exposed to show whether or not they were mud cracks.

Reserves.—On the assumption that the dimension along the strike is 2000 ft. and that along the dip 50 ft., the total thickness of available celestite rock 50 ft., and its density 3.9, the western part of the deposit would contain altogether about 600,000 tons of celestite of different grades. The amount of celestite in the eastern district that has escaped silicification should be added to this figure, but present work affords no basis for an estimate of the quantity.

Aguila

Location.—A large deposit of celestite occurs in the Vulture Mountains, Arizona, in the NW.¼ sec. 20, T.6N., R.7W., Maricopa County,

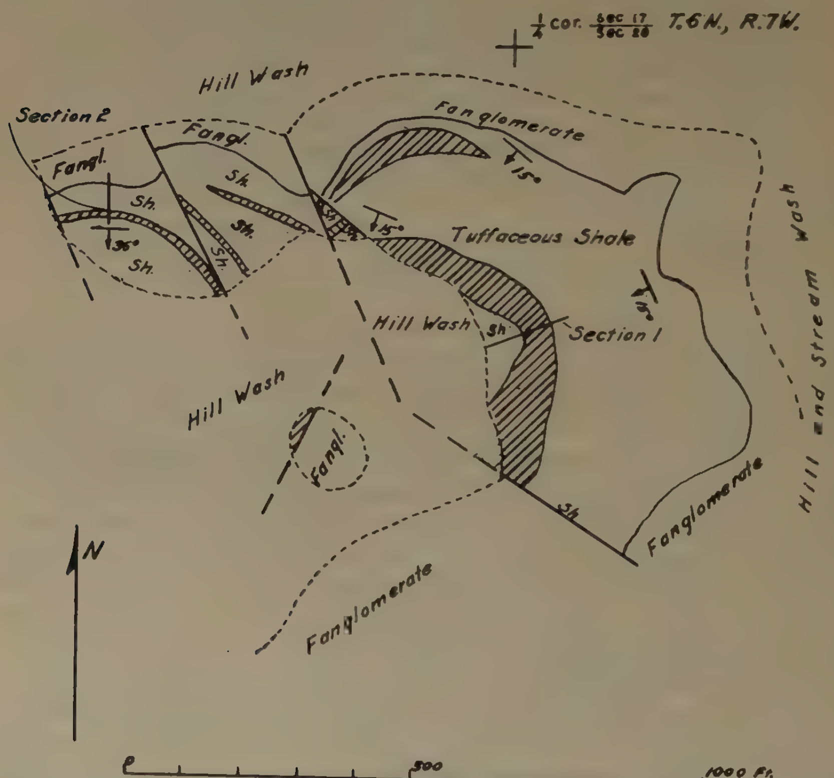

FIG. 3.—SKETCH SHOWING GEOLOGIC RELATIONS OF SOME OF THE CELESTITE (SHADED) CROPPINGS IN DEPOSIT NEAR AGUILA, MARICOPA COUNTY, ARIZONA.

about 15 miles southeast of Aguila. The deposit was discovered and is owned by Milton Ray, of Aguila, and has been described by Butler[2].

General Features of District.—The Vulture Mountains in the vicinity of the deposit are a low, rugged range made up of a series of volcanic

[2] B. S. Butler: Strontium Deposit near Aguila, Arizona. Dept. Interior *Press Mem.* 31445 (1929).

rocks of both siliceous and basaltic types, several thousand feet thick. The central part of the series, which is dominantly a shaly tuff, contains the celestite. Extensive faulting has given an intricate structural pattern to the rocks of the district.

Celestite.—The deposit itself occurs in a valley on the tip of a northeasterly spur on which may be seen several old terrace levels. Around the base of the spur (Fig. 3) is exposed a dark purple fanglomerate made up of granitic and volcanic debris. Resting on this is a shaly tuff, which extends about 100 ft. up to a narrow bench formed of resistant beds of celestite rock that weather out as a gray cliff. Above this bench the ground rises steeply to an old terrace level, from which material has been washed down over most of the hill slopes. More celestite rock is found southwest of the small area shown in Fig. 3, but the croppings are mostly hidden by hill wash. The celestite occurs as beds in the shaly tuff member at several horizons, as shown in Fig. 3. The sections (Table 3) show its mode of occurrence.

The beds of celestite rock form zones, which can be followed for distances of as much as 500 ft. but which are greatly disturbed by faulting. It was possible to trace some of the individual beds as much as 100 ft. on the surface, and it was found that interfingering into the tuffaceous shale, thickening and thinning of the beds and discontinuity prevailed here, as in the Argos deposit. The bedding is well marked, but the shaly tuff and celestite rock firmly adhere along contacts of the beds. In places the thicker beds show lamination marked by streaks of tuff and clay.

Silicification is prevalent in the district. The base of the tuffaceous shales is silicified for a thickness of 10 ft. or less. Some laminae are more silicified than others, and the resultant rock weathers to a rough, scabby material. Not only the shales have been silicified. The celestite zone just southwest of the quarter corner of secs. 17 and 20 is so intensely silicified that only small masses of celestite rock are left, and the original boundaries of the beds are obliterated. At other places beds of celestite rock pass into material weathering to horizontally fluted surfaces in which the silicified parts form the ridges and the celestite rock forms the grooves. In some places the bands of silica are so numerous as to suggest a laminated shale or shaly tuff in the state of incipient replacement by the celestite, as described by Butler[3]. A section of such material, however, under the microscope shows bands of fine-grained celestite and clay particles alternating with bands of celestite and fresh unaltered tuff particles. The fine-grained celestite and clay have been replaced by more coarsely crystalline celestite, which in turn has been replaced by chalcedony. In places the central parts of the veins of the coarser celestite contain quartz. Aside from the later recrystallization and silicification,

[3] Reference of footnote 2.

TABLE 3.—*Sections in Celestite Zone near Aguila, Maricopa County, Arizona*

SECTION 1, NW.¼ NE.¼ SEC. 20, T.6N., R.7W.

	Feet
Top of section in light brown shaly tuff.	
Interbedded shaly tuff and thin-bedded celestite rock	15.0
Medium-grained buff celestite rock, massively bedded	2.4
Light olive-buff shaly tuff, weathering brown	0.2
Massively bedded medium-grained buff celestite rock	0.8
Thin-bedded celestite rock and shaly tuff	1.2
Massively bedded medium-grained buff celestite rock	3.5
Thin-bedded celestite and shaly tuff	2.0
Massively bedded medium-grained buff celestite rock	1.2
Olive-buff shaly tuff, weathering brown	
	26.3

SECTION 2, NE.¼ NW.¼ SEC. 20, T.6N., R.7W.

	Feet
Alluvium with caliche capping.	
Yellowish green clayey tuffs	60.0
Thin-bedded fine-grained celestite rock; silicified laminae weather out as scabby brown bands	5.5
Shaly tuffs; details obscured by hill wash	11.0
Massively bedded medium-grained buff celestite rock	1.5
Olive-buff shaly tuff	0.1
Massively bedded medium-grained buff celestite rock	1.7
Olive-buff shaly tuff	0.1
Massively bedded medium-grained buff celestite rock	0.4
Olive-buff shaly tuff	0.1
Massively bedded medium-grained buff celestite rock	1.2
Shaly tuff with lenses and nodules of celestite rock	0.6
Shaly celestite rock	1.3
Massively bedded medium-grained buff celestite rock	1.0
Shaly tuff with nodules of celestite rock	1.0
Massively bedded medium-grained celestite rock	1.6
Shaly tuff	0.2
Medium-grained celestite rock	0.1
Olive-buff shaly tuff	1.0
Massively bedded medium-grained celestite rock	0.5
Olive-buff shaly tuff, weathering brown	3.7
Thin-bedded shaly tuffs hidden by hill wash; lower part contains celestite rock locally but is extensively though irregularly silicified	63.0
Dark red to purple fanglomerate formed of granite and volcanic rock debris	
	155.6

the celestite rock shows no features differing from other bedded precipitates or "evaporites."

Reserves.—Surface croppings and pits indicate that the celestite rock lies under an area of about 18,000 sq. yd. If the total thickness present

is assumed to be 9 ft., and no allowance is made for the variable dip of the beds, the total amount of celestite rock is about 180,000 short tons. More exists to the southwest of the area sketched in Fig. 3.

Gila Bend

Location.—Deposits of celestite in Maricopa County, Arizona, 15 miles from Gila Bend and about three miles east of Black Rock siding on the Tucson, Cornelia & Gila Bend Railroad, were first described by Phalen[4], who visited them in 1912, shortly after their discovery. The deposits were worked during the World War but appear to have been abandoned since then.

General Features of District.—The deposits lie on the northwest side of a low range of mountains, which rises from the plain on which Gila Bend is built. They occur in a series of tuffs from which the pediment of the mountains is carved and upon which rest the basaltic lavas forming the mountains. The deposits are covered at most places by a thin mantle of gravel.

Celestite.—Phalen describes the celestite as occurring with gypsum, sandstone and conglomerate and striking in a more or less northerly direction, with steep dips to the east over a distance of 5000 ft. Only the part that from Phalen's description represents the southern part of the zone was examined in this investigation. Here the celestite occurs in beds that crop out at several places over a distance of 750 ft., strike N.65°E. and dip 28°SE. The main bed is 2 to 3 ft. thick and can be traced for the entire distance, but at places there are less continuous beds interbedded with the tuffs, which bring the thickness of the zone up to a maximum of 6 ft. The material with which the celestite rock is interbedded is a sandy tuff containing numerous glistening biotite flakes and some grains of fresh olivine. The amount of this material differs at different places, and some of the less extensive beds grade from material that is mainly celestite into tuff. Such gradation, however, implies admixture of increasing amounts of fragmental material with the celestite rather than the replacement of tuff grains by celestite.

Reserves.—On the assumption of a length of 750 ft., a thickness of 2 ft., and a distance of 50 ft. on the dip, the amount of celestite rock present would be about 9000 short tons. If, as is probable, the celestite zone extends farther along the strike, this estimate would be greatly increased.

Avawatz Mountains

Location.—The celestite deposits of the Avawatz Mountains have been briefly described by Phalen[5] and have figured extensively in the

[4] W. C. Phalen: Celestite Deposits in California and Arizona. U.S. Geol. Survey *Bull.* 540 (1912) 531–533.

[5] Reference of footnote 4, 526–531.

literature of strontium deposits. The deposits are on patented claims belonging to the Avawatz Salt & Gypsum Co., of Los Angeles, Calif., on the northeast slope of the Avawatz Mountains, 25 to 30 miles by road from Riggs, on the Tonopah & Tidewater Railroad.

General Features of District.—The deposits occur in a series of Tertiary lake beds that contain extensive beds of gypsum and salt, and which form a gigantic sliver of rock about 10 miles long crushed between blocks of ancient crystalline rocks. The gypsum occurs along the entire length of the sliver, but the salt is concentrated near the center. The celestite apparently is restricted to two localities, according to J. E. Meyer, of Barstow, Calif., who conducted the prospecting and assessment work for the company. Traverses made across the section in the southern part seem to confirm this statement, as they failed to reveal any celestite.

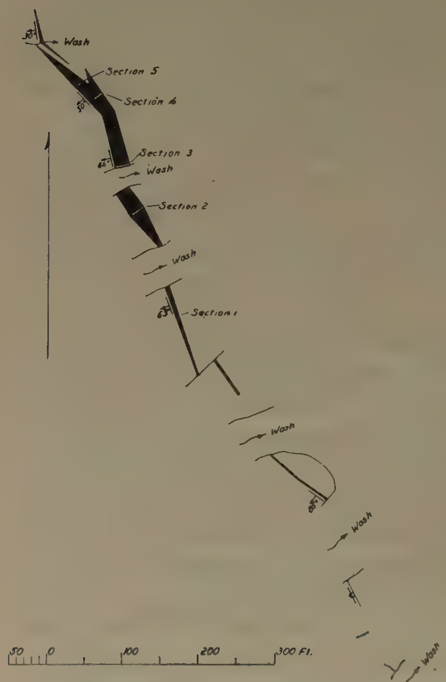

Fig. 4.—Plan of celestite croppings near center of sec. 24, T.18N., R.5E. (unsurveyed), Avawatz Mountains, San Bernardino County, California.

Celestite.—The larger of the deposits occurs in the extreme southerly tip of a low range of hills west of the Denning Spring-Confidence Mill road about four miles by road northwest of Denning Spring. The celestite occurs as a series of beds in a gypsum zone 20 to 30 ft. thick. Croppings may be traced for 1000 ft., but at each end the beds thin out and are represented by nodules in the gypsum. To the south this zone is covered by wash but to the north it may be traced several thousand feet by the celestite nodules and manganiferous beds, which weather as black streaks along the hillsides. Fig. 4 shows the plan of the beds, and the sections of Table 4 show the manner of occurrence of the celestite.

In the southern part of the zone the celestite is represented by a single bed of pure material about 6 in. thick bounded by sharp contacts with the gypsum. In the distance, from the south end of the zone to the locality of section 1, the bed increases to 3 ft. 3 in. in thickness, but it cannot be traced farther north because of the confusion caused by numerous small fractures (not shown on the map), which repeatedly

TABLE 4.—*Sections near Center of Sec. 24, T.18N., R.5E. San Bernardino Meridian (Unsurveyed), Avawatz Mountains, San Bernardino County, California*

SECTION 1 (MEASURED FROM WEST TO EAST)

	FT.	IN.
Top of section		
Gypsum	4	
Massively bedded medium-grained celestite rock	3	3
Green gypsiferous celestite rock		3
Gypsiferous celestite rock	2	2
Greenish gypsiferous clayey celestite rock		3
Massively bedded medium-grained celestite rock	2	2
Manganiferous, gypsiferous celestite rock	1	+
	13	+

SECTION 2 (MEASURED FROM WEST TO EAST)

	FT.	IN.
Top of section		
Gypsiferous celestite rock with manganese stains	3	
Gypsiferous celestite rock with nodular manganiferous masses at base	4	2
Gypsum	6	
Massively bedded medium-grained celestite rock		6
Gypsum with some nodules of medium-grained celestite	2	6
Massively bedded medium-grained celestite rock	2	6
Gypsum	2	
	20	8

SECTION 3 (MEASURED FROM WEST TO EAST)

	FT.	IN.
Top of section		
Gypsum		
Massively bedded medium-grained celestite rock, manganiferous at base	3	6
Massively bedded medium-grained celestite rock	2	6
Manganiferous gypsum	1	6
Massively bedded medium-grained celestite rock, manganiferous	1	
Gypsum with nodular masses of medium-grained celestite	6	4
Massively bedded medium-grained celestite rock	1	7
Interbedded celestite rock and gypsum		6
Gypsum	5	6
Gypsiferous clays.		
	22	5

COMPOSITE SECTION (MEASURED FROM WEST TO EAST)

	FT.	IN.
Top of section		
(Section 5)		
Manganiferous gypsum, with masses of medium-grained celestite rock near base	4	
Gypsiferous and manganiferous celestite rock	2	
Manganiferous gypsum; contains much celestite in scattered crystals	1	6

TABLE 4.—(*Continued*)

(Section 4)

	Ft.	In.
Gypsum with reniform nodules of medium-grained celestite....	11	
Nodules of medium-grained celestite, forming bed...........		6
Gypsum..	4	
Massively bedded medium-grained celestite rock............		3
Gypsum..	4	
Gypsiferous clays.		
	27	3

offset the beds. Other beds in sections 3, 4 and 5 have centers of rather pure material but grade at the top and bottom into gypsiferous celestite rock and gypsum. The persistence of the bodies of celestite rock and their demarcation entitle them to be called beds.

The second locality is in the easternmost part of the hills just north of the Saratoga Springs-Denning Spring road. The celestite occurs in lenses and lenticular beds in a series of sand, clay and gypsum, which caps an irregular hill about 1000 ft. long and 300 ft. wide. The section shown in Table 5 was measured on the southeast corner of the hill, in beds exposed in a prospect trench.

TABLE 5.—*Section in Celestite Zone, Avawatz Mountains, San Bernardino County, California*

NORTHEAST CORNER SEC. 27, T.18N., R.5E. SAN BERNARDINO MERIDIAN (UNSURVEYED)

	Feet
Summit	
Thin-bedded gypsum with lenticular beds of celestite as much as 6 in. thick forming ¼ total thickness........................	3
Gypsum with a few celestite lenses............................	6
Green tuffaceous clay and sandy tuff with lenses of celestite 1 to 16 in. thick and as much as 10 ft. in length........................	20
Green clay and sandy tuff..................................	
	29

The lenses of celestite that occur in the sediments are of particular interest because they show no signs of replacement but apparently are the result of deposition of masses of crystalline celestite and gypsum as a chemical precipitate.

Reserves.—In the western body an estimate based on a thickness of 2 ft. of celestite rock for a distance of 1000 ft. on the strike and 50 ft. on the dip gives 12,000 short tons. If the beds increase or decrease in thickness with depth the estimate will be affected materially. The eastern body is not regarded as of commercial importance.

Fish Mountains

Location.—A deposit of celestite associated with gypsum occurs in the Fish Mountains of the Salton Sink, in sec. 18, T.13S., R.9E., Imperial

County, California, about 26 miles north of Plaster City and one mile east of the gypsum quarries of the Pacific Portland Cement Co.

General Features of District.—The Tertiary sedimentary section in this district is represented by patches of a very thick gypsum bed, which rests on deeply weathered granitic rocks. The gypsum may be related to the marine Miocene rocks of the Coyote Mountains, to the south.

Celestite.—The celestite rock forms a ragged, dissected capping of nearly flat-lying beds on an isolated hill of the gypsum. A section measured on the southwest corner of the hill is shown in Table 6.

TABLE 6.—*Section in Celestite Zone, Fish Mountains, Imperial County, California*

SEC. 18, T.13S., R.9E.

	FEET
Summit	
Celestite rock, massive, white	10
Interbedded gypsum and celestite	3
Gypsum; a few nodules of celestite near top	100
Deeply weathered granite.	
	113

The celestite rock is uniformly pure and is free from silicified material. It is not known whether continuations of the bed exist at other places in the district.

Reserves.—The ragged capping on the hill contains more than 10,000 tons of celestite rock.

Other Occurrences of Celestite

Celestite crystals were collected from the old colemanite workings at Borate City, in the Calico Mountains, San Bernardino County, California, and it is reported that beds several inches thick occur there. Celestite is also reported as occurring with colemanite at Ryan, Calif. Unverified statements have been made regarding a large deposit of celestite in Cadiz Dry Lake, in secs. 11 and 12, T.2N., R.15E., San Bernardino County. It is possible that other deposits of commercial size occur in the Tertiary beds of this region.

Mineralogy and Chemical Analyses of the Celestite Deposits

The celestite of the deposits described occurs as a bedded rock, which by admixture with clay, tuff fragments and gypsum grades into other rocks. The essential mineral is celestite. Usually it is more or less silicified and where weathered is partly altered to strontianite. In many places small amounts of manganese oxides occur with the celestite.

In the Fish Mountains and Avawatz Mountains the celestite occurs with gypsum. Gypsiferous facies show euhedral crystals of celestite embedded in a matrix of gypsum or of anhydrite altering to gypsum.

(Fig. 5). Celestite in the masses representing purer material does not show well developed crystal outlines.

In the deposits of Gila Bend, Aguila and Argos, the celestite is associated with clay and tuff fragments. It forms regular beds and grades into tuff containing no celestite. In places the finely laminated beds are distorted. Under the microscope much of the original material of the rock appears to be a mixture of fine-grained celestite with clay. Some laminations show a large number of tuff particles. Different laminae contain different proportions of clay and celestite and different-sized grains of celestite. Although a part of the coarser grained celestite, 0.5 to 2 mm. in diameter, may be original, most of it has been formed by recrystallization from finer material of the groundmass, which in the coarser grained specimens is represented by isolated patches (Figs. 6 and 7). In some samples masses of the larger celestite grains are connected by veinlets of celestite cutting the laminae of the finer groundmass.

Silicification is prevalent. Most of the silica is in the form of small spherulitic masses of chalcedony, which has replaced the celestite. Only a small part of it is represented by quartz, and usually this is found filling the centers of the celestite veins.

Many samples show incipient alteration of the celestite to strontianite, probably due to weathering. Manganese oxides are common and appear to have been concentrated locally by ground waters.

In all specimens examined the small fragments of feldspar, quartz, biotite, chlorite, and locally olivine, in the celestite rock are sharply bounded and show no evidence of replacement by celestite. Unlike the strontianite rock, this material shows no relict structures suggesting that it has replaced a host rock.

Chemical Analyses.—Chemical analyses have been made of several of the samples collected and are given in Table 7 together with analyses taken from reports by Butler, Knopf and Phalen. These analyses closely reflect the composition of the rock as indicated by the microscope. The large amounts of silica present in some samples are due to excessive silicification rather than to excessive amounts of clastic particles. High percentages of carbonate reflect high strontianite content.

Origin of the Celestite Deposits

Most of the world's deposits of celestite are of replacement origin and are relatively small[6]. The strontium is believed to have been derived by circulating waters from the surrounding rocks and originally from the ocean.

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[6] For excellent bibliographies see W. Noll: Geochemie des Strontium, in Planck und Linck, Chemie der Erde, **8**, 595–600, 1934; K. Andree: Ueber den Coelestin im Mukattamkalke von Ägypten. *Neues Jahrb. Min.* (1914) **37**, 369–374.

TABLE 7.—*Analyses of Celestite Rock from Southeastern California and Western Arizona*[a]

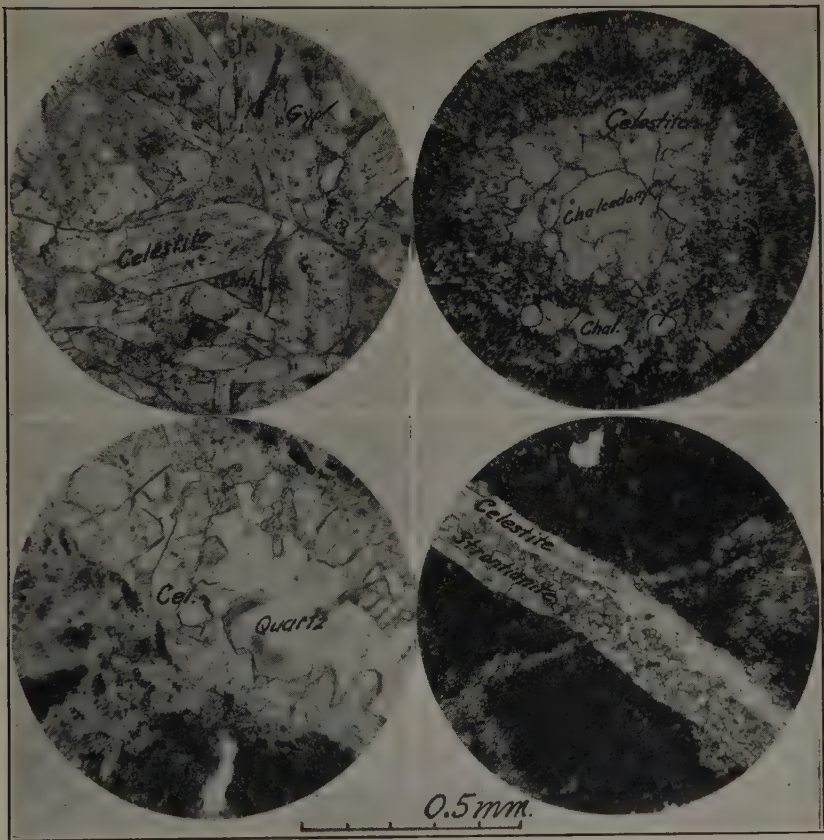
District	Location	No.	Per Cent by Weight											$SrSO_4$ Calculated from SrO
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	CO_2	H_2O	SrO	BaO	MnO	
Argos	Section 1, sample 1	1	2.05	0.45	0.15	1.55		40.80	Little	0.50	50.50	0.13	None	89.5
	3	2	2.80	0.55		0.75		41.20	Little	0.55	51.55	0.63	0.005	91.4
	4	3	7.05	1.80		1.65		37.30	Little	1.10	47.75	0.26	0.02	84.6
	5	4						34.34	None		43.35	0.64	Trace	76.8
	6	5						38.33	Trace		48.53	0.73	Trace	86.0
	Section 2, sample 1	6	18.02	0.66	0.05	0.96		34.49	0.03		44.35	0.09	None	78.5
	2	7						35.85	None		44.39		None	78.6
	3	8						41.41	0.70		50.53		None	89.6
	4	9						29.88	Trace		36.16	1.70	Trace	64.1
	5	10						31.52	7.90		39.52	0.76	0.17	70.0
	6	11						36.89	1.40		45.29	0.51	0.05	80.3
	7	12	17.86	0.98	0.38	2.81	0.17	31.49	0.27	1.60	40.55	1.19	Trace	72.0
	8	13	2.20	0.21	0.46	5.34	0.08	36.88	4.05	0.03	47.73	1.14	0.02	84.6
	9	14	1.53	0.92	0.54	0.97	0.11	41.08	0.30	0.56	52.35	1.07	Trace	92.6
Fish Mountains	Representative sample	15	0.90	0.49	0.50	2.47	0.05	41.44	0.71	0.16	52.88	1.53	Trace	93.8
Gila Bend	Main workings	16	5.82	0.66	0.57	1.89	0.23	36.91	2.13	0.53	49.97	0.98	Trace	88.5

TABLE 7.—(*Continued*)

District	Location	No.	Per Cent by Weight											$SrSO_4$ Calculated from SrO
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	CO_2	H_2O	SrO	BaO	MnO	
Avawatz Mountains[b]		17				0.75		42.38	0.92		50.99	Trace		90.4
		18									38.41			68.1
		19									47.92			84.9
Gila Bend[c]		20									49.36			87.5
		21									48.99			86.9
Aguila[d]	Selected sample	22	12.91	None	0.39	0.41	None	36.70	0.57		48.10	None		85.3
	Average	23	22.1			0.29					41.26	0.33		73.1

[a] Analysts: R. K. Bailey, Nos. 1 to 3; R. C. Wells, Nos. 4, 5, 9, 10, 11; C. Milton, Nos. 12 to 16; R. E. Stevens, Nos. 6 to 8.
[b] W. C. Phalen: Reference of footnote 4, 530.
[c] W. C. Phalen: Idem, 533.
[d] B. S. Butler: Reference of footnote 2.

The mineralogy, structure and stratigraphic features of the deposits described here indicate that the celestite was formed as a chemical



5 6 7 8

FIG. 5.—GYPSIFEROUS CELESTITE FROM THE AVAWATZ MOUNTAINS, CALIFORNIA.
Celestite crystals in matrix of gypsum clouded by minute anhydrite grains. It is believed anhydrite was deposited with celestite and that gypsum is due to later alteration.

FIG. 6.—CELESTITE FROM DEPOSIT NEAR AGUILA, ARIZONA.
Dark groundmass of fine-grained celestite and clay particles in which have formed masses of coarser grained celestite, which in turn are replaced by silica (chalcedony).

FIG. 7.—CELESTITE FROM DEPOSIT NEAR AGUILA, ARIZONA.
Veinlet of celestite replacing fine-grained clay and celestite groundmass. Center of veinlet is filled with quartz.

FIG. 8.—STRONTIANITE FROM BARSTOW, CALIFORNIA.
Dark portion represents mass of small strontianite grains. Vein cutting strontianite contains celestite bordered by strontianite. Bright patch is grain of unaltered quartz. Light patches on either side of veinlet formed of coarser grained strontianite than dark portion.

precipitate in small ponds, in lakes, and perhaps, in the Fish Mountain deposit, in a lagoon. Although there is evidence of recrystallization of some of the material, no field evidence has been found to suggest that the celestite has replaced another rock. Microscopic examination supports

the hypothesis of its origin as a chemical precipitate. There is nothing unique in such an origin, so far as deposits already described in the literature are concerned, but these deposits are unique in their size.

The improbability that ground waters could contain sufficient concentrations of strontium salts to form large deposits consisting essentially of celestite, such as that at Argos, has already been mentioned. However, the region in which the deposits occur exhibits several features that seem suggestive as to the source of the strontium; namely, volcanism during the deposition of the celestite, the presence of large borate deposits suggestive of solfataric activity in the region, and the occurrence of numerous barite veins.

Noll[7] has pointed out that strontium is concentrated in the rest magma during the crystallization of igneous rocks. In view of the constant association of barium and strontium in quantities of the same order of magnitude in magmas, it would seem that when much barium is released comparable amounts of strontium may be given off also. The source of the strontium in the Sicilian celestite deposits has been supposed to be submarine solfataras[8], and strontium is known to occur in many springs.

It is suggested that the source of the strontium of the celestite deposits of southeastern California, southern Nevada and western Arizona was in the volcanic rocks of the region. As to the chemistry and physics of the process of deposition, no hypothesis is offered here. The insolubility of barite has led Noll[9] to believe that it takes little part in the secondary cycle. The presence of barite in these deposits, as shown by the analyses, would suggest that the material was transported no great distance. It is possible that precipitation of barite in veins was the first step, and that the resultant solutions rich in strontium but poor in barium deposited their strontium and barium content in near-by ponds and lakes by precipitation from sulfate waters. The more soluble minerals were carried away, perhaps, in such deposits as that at Argos, but in such deposits as those of the Avawatz Mountains gypsum was deposited with the celestite.

Utilization of the Celestite Deposits

In these deposits there is much material that is more than 90 per cent strontium sulfate, which could be shipped and manufactured with little difficulty. Development of a large industry, however, would involve the use of material containing from 70 to 90 per cent of strontium sulfate. The chief impurity is silica. This dilutes the ore but because of its

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[7] W. Noll: Reference of footnote 6, 556–557.

[8] G. Spezia: Sull' origine del solfo nei giacimenti solfiferi della Sicilia, 52–62. Torino, 1892.

[9] W. Noll: Reference of footnote 6, 558 (footnote).

inertness may be less troublesome than similar or smaller quantities of lime. Another problem is the recovery of the thinner bedded material, of which there is a large amount in some deposits.

The cost of mining these deposits should be low, because the beds are fairly regular and the ground stands well. Although the shaly tuffs and clays weather to loosely pulverulent soil, they are surprisingly strong where exposed in workings protected from the weather.

The region is barren and relatively unsettled, but the known deposits are rather easily accessible. Existing freight rates on limestone in this region suggest that rates on celestite rock would be reasonable.

Aside from the relatively small market for strontium pharmaceuticals, reagents, and in pyrotechnical manufactures, the main potential market is the beet-sugar industry. It is possible that a large assured cheap supply of domestic strontium hydrate might awaken interest in the Scheibler process of desaccharizing beet-sugar molasses in the Colorado and California fields, neither of which is far from the deposits. If a use should be found for metallic strontium, the power resources at the Boulder Dam would make possible the production of large amounts of the metal at low cost.

Strontianite Deposits

Strontianite is known in the region of southeastern California and western Arizona only as the alteration product of celestite or in concretionary masses formed by precipitation of the strontium content of ground waters. It has been recognized as the product of weathering of celestite in thin sections of celestite rock from all the deposits described above, and it forms the cement of some of the tuff associated with the celestite rock at Gila Bend. It is probable that many of the concretions in the shaly tuffs of the celestite deposits contain some strontianite. However, the locality near Barstow is the only one in which sufficient material of requisite purity has been found to warrant prospecting.

Barstow

Location.—Strontianite deposits occur about 10 miles northeast of Barstow, San Bernardino County, California, in low hills in secs. 29 and 30, T.11N., R.1W. Patented claims covering the richer parts are owned by L. G. Henderson and T. G. Nicklin, of Barstow. The deposit has been described by Knopf[10].

General Features of District.—The deposits occur in a series of beds known as the Barstow formation, regarded as of upper Miocene age. The lower part in this district consists of several thousand feet of fanglomerate formed chiefly of granitic debris with thin layers of volcanic

[10] A. Knopf: Strontianite Deposits near Barstow, California. U.S. Geol. Survey *Bull.* 600 (1918) 257–270.

ash. Above this is a series of tuffaceous shale and clay, more or less calcareous and several hundred feet thick, in which the strontianite occurs. These beds are overlain by more indurated tuff, shale and limestone.

Strontianite.—Strontianite occurs in this district both as elongated nodular masses following the bedding planes of the shaly tuff and clay and as concretions, which transect the bedding and appear to have replaced the shaly tuff and clay. Most of the strontianite bodies are small and contain less than one cubic yard of material. Several varieties of strontianite rock are present. The most common is light gray and resembles a very much hardened clay. Other varieties are finely crystalline and contain tiny dark brown to black spherulitic masses. The purest material consists of small radiating crystals of dark amber to brown strontianite.

Reserves.—Small amounts of strontianite rock can be obtained by "gophering" after masses in the weathered material near the surface, but the expense of digging in the extremely tough shale and tuffaceous clay makes prospecting too expensive for the development of commercial quantities, even if they exist. According to Mr. Henderson, most of the material shipped in the war period (1914–1918) was so badly sorted that the $SrCO_3$ content amounted to only 35 per cent and was rejected by purchasers.

Mineralogy.—Under the microscope the material of the light-gray concretions is seen to be a mass of fine grains of strontianite and clay with particles of other minerals of clastic origin. Lamination is apparent, and there are small obscure spherulitic masses of strontianite. The darker material shows less clay, the strontianite is more commonly formed into spherulitic masses, and there appears to be an incipient increase in grain size. In the section examined a veinlet of celestite was found cutting across the strontianite (Fig. 8).

Origin.—It is believed that the strontianite bodies were formed by precipitation of strontium as carbonate from sulfate solutions representing concentrations derived from small quantities of celestite originally in the shale. The undisturbed nature of the laminae of the shaly tuff and clay surrounding the nodular masses of strontianite along bedding planes suggests that the strontianite in these bodies has replaced its enclosing rocks, as has the strontianite of the concretions. Presumably the clay material was removed as strontianite was deposited. The process doubtless was similar to that involved in the formation of concretions in the shaly tuff at other places.

The analyses of material from different localities illustrate steps in the process here suggested (Table 8). Analyses 3 and 4 are particularly interesting in that they show notable increases in the concentration of strontia, manganese and carbonates in the concretions as compared

with the enclosing shaly tuff, although there is no concentration in the barium content, indicating that barium sulfate is too insoluble in sulfate solutions of the type involved to play a part in such processes. Analyses 1 and 2 represent the end products of the process.

TABLE 8.—*Analyses of Strontianiferous Materials from Argos and Barstow Districts, California*[a]

Material No.	Percentages							
	SiO_2	Al_2O_3	CaO	SO_3	CO_2	SrO	BaO	MnO
1			6.40	0.05	n.d.	60.99	None	
2	5.59	1.17	5.19	0.28	28.18	55.2	None	
3				0.26	28.10	3.29	Trace	0.62
4				0.29	1.44	0.06	Trace	0.01

[a] R. C. Wells, Analyst. Analyses 1 and 2 made in 1918; 3 and 4 in 1934.

1, 2. Partial analyses of strontianite from Strontium Hills, California. A. Knopf: Reference of footnote 10, 260, 262.

3. Analysis of nodule from Argos, Calif.; see section 1, Table 2.

4. Analysis of shale enclosing nodules, Argos, Calif.; see section 1, Table 2.

Bajada Placers of the Arid Southwest

By Benjamin N. Webber,* Member A.I.M.E.

(New York Meeting, February, 1935)

Many of the auriferous placers of the arid Southwest differ widely from the standard types of stream and eluvial deposits of more humid regions, although exhibiting some of the features of each. This divergence in characteristics is of geological and economic importance and appears sufficient to warrant the consideration of these placers as a class distinct from both stream and eluvial deposits. It is hoped that the consideration of these auriferous gravels as a distinct type of deposit will facilitate recognition of morphological and economic features that might remain obscure if these deposits were viewed in the light of stream or eluvial placers whose type locality is a more humid environment.

"Bajada placer" is proposed as the designation for this type of placer deposit. Bajada is the Spanish term for slope and is used locally in the Southwest to indicate the lower slope of a mountain range, the portion consisting of rock debris and standing at a much lower angle than the rock slope of the range proper. It has been used in a geologic sense by Schrader[1] and others. The type locality of bajada placers is the Sonoran Desert,[2] where they occur on the bajada or rock debris slope of desert ranges. Stream placers are represented in the Southwest, but most of them lie within the mountain topographic province, the Mexican Highlands[2] section of the Basin and Range physiographic province. Eluvial placers may occur in the mountainous semiarid Mexican Highlands but are almost unknown in the extremely arid Sonoran Desert, as mountain slopes are generally too steep to permit the accumulation of any considerable mantle of residual debris. Since their salient distinctions are almost wholly the result of formation under conditions of extreme aridity, bajada placers are largely confined to the Sonoran Desert, although a few occur in the adjacent Mexican Highlands. They may be modified by the action of ephemeral streams, in which case the placer gravels of these arroyos approach stream placers in type and habit of occurrence, but their relation to an arid environment and the bajada type is usually apparent.

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[1] F. C. Schrader: Mineral Deposits of the Santa Rita and Patagonia Mountains. U.S. Geol. Survey *Bull.* 582 (1915) 36.

[2] N. M. Fenneman: Physiography of the Western United States. New York, 1931. McGraw-Hill Book Co. (Fenneman's physiographic nomenclature is used throughout.)

The total production of gold from bajada placers in the southwestern United States is necessarily small, probably not over ten million dollars. Placer mining in Arizona and New Mexico was greatly handicapped by Indian trouble until about 1880. Practically the entire production from bajada placers was the result of the rudest sort of *gambucino* operations by the individual or small-group efforts of independent *entrepreneurs* utilizing such small-scale methods as the pan, rocker, hand-bellows dry washer, and in some instances sluicing during an ephemeral runoff in a favorable season. The factor that militates against operation to the greatest extent is lack of surface water. Water is not available for small-scale operations on most bajada placers except during extremely limited periods following infrequent rains. Attempts to work these placers on a large scale have been mostly promotional ventures that proceeded with a cheerful disregard of the geological and other natural phenomena involved and often with a complete lack of knowledge of the quantity and tenor of material available.

The genesis of a bajada placer is basically similar to that of a stream placer except as it is conditioned by the climate and topography of the arid region in which the placer occurs. Climate and topography influence rock decay, weathering, transportation and deposition to the end that bajada placers are a considerably modified form of the equivalent deposits of a humid region.

Both climate and topography of the Sonoran Desert and their influence on erosion are ably described elsewhere and only the briefest résumé as a background of the bajada placer will be attempted here.

Climate and Topography of the Sonoran Desert

The Gila Desert of southwestern Arizona constitutes a considerable portion of the Sonoran Desert and contains a large number of the bajada placers of the Southwest. The precipitation over the Gila Desert is the least in the United States. The average annual precipitation may reach a maximum of 10 in. in the higher altitudes but approximates 3 in. over most of the lower regions. The lowest average annual rainfall recorded is 2.47 in. The average for the region is between 3 and 5 in. The humidity is characteristically low and evaporation from free water surfaces is the highest recorded in the United States. In this region there is a tendency for all the annual precipitation to be concentrated into brief, local, violent rainstorms with a rapidly shifting locus. In southwestern Arizona and northwestern Sonora, where the average rainfall approaches 3 in. per year, many wide areas will have no seasonal storms capable of inducing an hour's flow in the arroyos or dry washes, and storms of cloudburst intensity capable of supplying a sufficient volume of water to fill the normally dry drainage channels for a few hours

may be decades or centuries apart. In this region rainfall is a direct function of altitude, increasing at an average rate of 0.3 in. of mean annual precipition for each increase of 100 ft. in elevation. This direct variation is just as pronounced for elevations below 1000 ft. as in higher elevations. Above 4000 ft. there is a distinct tendency for the rainfall-altitude curve to flatten as the rate of increase in precipitation per unit elevation tends to decrease.

In the mountain ranges of the Gila Desert, runoff is a higher percentage of the total precipitation than in more humid regions. Vegetation is very sparse or wholly lacking, consequently transpiration, which may reach 40 per cent of the total precipitation[3] in forested regions, is negligible. As bedrock exposures cover practically the whole area of desert ranges, seepage subtracts but little from the runoff until it reaches the debris slopes at the foot of the range. Evaporation is high but since slopes are steep and the runoff unimpeded by vegetation and therefore rapid, evaporation has only a short period in which to act before the runoff reaches the foot of the range.

Temperature ranges in this area are extreme. A maximum of 120° F. contrasts with an occasional minimum of 10° F. The diurnal range in temperature in the Gila Desert is often between 50° and 60°. These ranges in temperature make insolation one of the most important weathering processes of the region.

The Pleistocene and late Tertiary climate of this region are considered as generally arid. In the Quaternary period, aridity seems generally indicated. There is some conflicting evidence concerning the climate of Pliocene time although Tertiary sediments in general indicate at least moderate aridity. The Gila conglomerate, Pleistocene, is a widespread fanglomerate type of formation reaching its greatest development near the southern boundary of the Mexican Highlands but extending into the Gila Desert. The Gila conglomerate shows a preponderance of mechanical over chemical weathering in the processes that produced its constituents and a lack of sorting and bedding indicative of rapidly shifting, overloaded, torrential, ephemeral streams, which deposited their burden close to the foot of the mountains from which it was derived. This suggests an arid region not greatly different from the same region at present. Many undated Tertiary and Quaternary sediments occur in the Sonoran Desert and most of these indicate a generally arid climate at the time of their deposition. The Temple Bar conglomerate is a widespread formation in the Sonoran Desert and presents almost the same aspects of aridity as the Gila conglomerate. The age of the Temple Bar remains in some doubt although it is indicated to be Pliocene, on

[3] R. Zon: Report of National Waterways Commission 1912. *Senate Document* 469, 62d Congress, 2d Session.

inconclusive fossil evidence.[4] The Pliocene lacustrine beds of the San Pedro Valley, Arizona, have yielded a number of vertebrate fossils, and on the basis of this fauna Gidley[5] regards the climate as warm and moist, similar to that of southern Mexico today. The present topographic expression of the Sonoran Desert is that of a far advanced arid cycle of erosion.

The topography of the Sonoran Desert is characterized by elongated mountain ranges rising abruptly without foothills from gentle debris-covered slopes and separated by wide detritus-filled valleys or bolsons. Typical playas or undrained basins are not numerous. Drainage is centripetal to the Gulf of California but, owing to extreme aridity, very little water from this region reaches the sea. The Gila and Bill Williams Rivers cross the region but carry water derived from the adjacent Mexican Highlands or Colorado Plateau. Mountains vary in size from small isolated hills to ranges that reach over 4000 ft. above the sea. There is great diversity of opinion as to the genesis of these mountains, as an advanced erosion cycle has tended to obscure their origin. The writer is of the opinion that the great majority may be interpreted as eroded fault blocks. In western Arizona, fault-block mountains become increasingly apparent northward. Some of the intermontane basins, or bolsas, are deeply filled with detritus from the hills. Borings near Wickenburg, Ariz., have penetrated 600 ft. of unconsolidated material and as high as 1800 ft. are reported elsewhere. A considerable number of desert ranges rest upon a rock pediment,[6] a gentle rock slope without any large amount of alluvial cover. Ranges that do not show a pediment at the base may have a buried pediment concealed by an increase in detritus contributed to the basin, causing the basin level to rise and inundate the pediment. Fluctuations in balance between debris from the immediate hills and rising or lowering basin levels are common.

Erosion

Erosion, transportation and deposition in a region of extreme aridity present some phenomena not encountered in more humid areas. Practically all the work of running water is strongly conditioned by aridity. The total lack of perennial streams and their erosional results is occasioned by the low volume of precipitation. The behavior of ephemeral streams is likewise influenced by local conditions. The larger part of the precipitation falls in the higher altitudes, where steep slopes, lack

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[4] N. H. Darton: Résumé of Arizona Geology. Ariz. Bur. Mines *Bull.* 119 (1925) 164–65.

[5] J. W. Gidley: Fossil Proboscidea and Edentata of the San Pedro Valley, Arizona. U.S. Geol. Survey *Prof. Paper* 131.

[6] K. Bryan: Erosion and Sedimentation in the Papago Country. U.S. Geol. Survey *Bull.* 730-B (1923) 52–58.

of vegetation, soil cover and seepage throw practically the entire rainfall into rock channels descending the range at a high gradient. Rapidity of both rainfall and runoff tend to produce violent floods of short duration. When these floods reach the foot of the range, seepage, which is negligible in the mountain area, becomes a formidable obstacle to the movement of surface water. Loss by seepage of these floods is so rapid that attempts to measure the rate of loss have failed.[7] The rate of seepage is so rapid that only an exceptional flood will persist far from the foot of the range. An exception to this is a partly dissected pediment, where dissection has advanced so far that the arroyos are entrenched in narrow rock-cut channels in the pediment. The rapid rate of seepage in the bajada area creates another phenomenon of aridity, the sheet flood. This flood is unknown in humid lands and nowhere reaches the importance it does in the Southwest. Water from an occasional violent rain is dumped on the bajada slope at the foot of the range, part may find its way into channels leading toward the center of the basin but since a large portion of a bajada slope consists of gently inclined planes, runoff water advances down the planes in sheets. The sheet flood picks up loose material on the surface and is continuously overloaded, tending to fill channels as fast as they may be formed and thus to maintain the planar surface of the bajada slope. Seepage loss is high in this area and the volume of water rapidly diminishes, sometimes to the point where the sheet flood becomes a mud flow. These sheet floods seldom extend far, although, following storms of exceptional violence, they may reach a mile or over in length. They are characterized by rapid accretion in volume and equally rapid diminution.

While the wind accomplishes less in net result of erosion and transportation than running water, nevertheless it is of great importance in this region, particularly in transportation. No one who has witnessed a sandstorm in the region can fail to be impressed by the quantity of solids in motion, and one who returns after a few months to an unfinished survey to find the notations on his stakes made illegible by sandblasting cannot fail to be almost equally impressed by the wind's corrasive action. Windstorms of violence are not the full measure of the transporting power of the wind; even slight and erratic breezes will lift a curl of dust and sand a foot or so off the ground, possibly to slacken and drop the load in some tens of feet. This action of the wind is almost continuous. The layer of fine material left by sheet floods and mud flows is scarcely dry before the wind begins to remove and dissipate the material.

Insolation is another process that reaches great importance in this region of extreme seasonal and diurnal range in temperature. Its results are spalling and exfoliation of rocks, particularly those of a

[7] W. N. White: The Ground Water Supply of the Mimbres Valley, New Mexico. U.S. Geol. Survey *Water Supply Paper* 637-B (1931) 77.

nonhomogeneous character. Unequal expansion and contraction of rocks on the bajada surface tend to maintain the surface material in a loosened condition, which facilitates the work of the wind and sheet floods in removal of finer material. The immediate result of this continual removal of fines on the bajada slope is a pavement of small rock spalls coated on one side with black satiny manganese oxides (desert varnish). Small, burrowing animals, numerous in the desert, are probably an appreciable erosive factor in supplying fresh loose material amenable to reworking by both wind and water.

Chemical weathering depends upon the presence of atmospheric and ground water and probably is less important in arid regions than elsewhere. The oxidation of the porphyry copper deposits of Arizona is evidence of the chemical work of atmospheric water on its way to permanent ground-water level, but few of these secondary orebodies are related to the present topography. The largest part of oxidation was accomplished under topographic conditions different from those of the present, and possibly different climatic conditions also.

Geology

Most all bajada placer gravels are Quaternary and the larger part are recent. The Pleistocene age of some of the terraces of the lower Gila River strongly suggests that some of the older and usually cemented auriferous bajada gravels may be Pleistocene. Portions of the Gila conglomerate, Pleistocene, are known to be auriferous but have nowhere yet proved commercial. The writer is not aware of the existence in the southwestern United States of auriferous bajada gravels older than Pleistocene.

The genesis of a typical bajada placer concerns the history of the gold from the time it, or the matrix containing it, is detached from its parent outcrop to the time it comes to rest on the bajada slope, a chronicle somewhat as follows.

Fissure veins probably yield most of the placer gold although other types of lode deposits contribute a certain quota, particularly pyritic replacement deposits. It seems doubtful whether a commercial bajada placer would result from the erosion of a number of auriferous veinlets or stringers, such as occasionally give rise to stream placers, unless the stringers were closely spaced and very rich. Limitation in area of origin and degree of concentration of bajada placers, in which the area of collection is limited to a part of the adjacent mountain range and concentration is retarded and finally almost arrested by factors of aridity, make it necessary to postulate one or several lodes of at least moderate size and tenor and probably containing oreshoots of unusual richness.

The outcrops of these lodes and their orebodies are acted upon by the agenda of erosion of an arid cycle. Insolation probably plays the

major role in disintegration; it is aided by rainfall and wind action. Angular boulders and spalls are detached from the outcrop. These lie on a steep slope, particularly in hard, crystalline, widely jointed rocks and often in closely jointed rocks and sediments. Some of these spalls are too large to be moved by the infrequent rains, violent as they may be, but start their journey to the bajada slope after insolation has reduced their size. They are moved by gravitational creep aided at intervals by the lubrication of runoff water and occasionally greatly accelerated in their progress by gullying of torrential rains of cloudburst intensity. Disintegration by insolation and other agencies continues and by the time the material reaches the level of the intermont drainage it is greatly reduced in size of particle, depending on the length of the journey. Probably the largest spall will be less than one foot in diameter. Boulders of many tons may be observed in rock-cut channels in the hills but these will not be moved until weathering has reduced them in size, and they represent but a small fraction of the material moved through these rock channels. Boulders and spalls 2 ft. in diameter do reach the bajada slope but the majority of the spalls are much smaller. By the time the vein matter has reached the level of the intermont drainage, each fragment originally detached from the lode has been reduced to a number of fragments and possibly 50 per cent of the gold has been released. The transportation of the material has been accomplished directly or indirectly by runoff, but reduction in size of particle has been largely effected by weathering agencies, principally insolation, and subordinately by transporting agencies.

When the rock fragments reach the level of the intermont drainage there occurs a change in the ratio of importance between transportation and weathering as factors in reduction, although it is doubtful whether the attrition of transportation ever becomes of equal importance with weathering as a reduction factor. Material in drainage channels is moved by erratic flash floods. These may remove finer material but move larger fragments by stages. The intervals between these floods are long and larger fragments are subjected to weathering processes en route. Rock-cut canyons of steep gradient in the interior of desert mountains are usually quite bare of rock detritus. Spalls, small enough to be removed, are swept downward by the first flash flood. Fragments too large to be moved by the volume of any given flood are reduced in size by weathering until they are capable of being moved, and moved in stages, being constantly weathered until they are dumped on the bajada slope. The distance through which debris is transported through intermont drainage by flash floods is short. The direct distance from the summit of a Sonoran Desert range to its bajada slope is seldom over 2 miles. In the adjacent Mexican Highland section this distance increases.

Rock-floored canyons through which rock fragments are moved by infrequent torrential floods should constitute excellent pebble mills for the further reduction of the material, but the amount of attrition accomplished seems to be slight, as fragments, large or small, on the bajada slope are decidedly angular and show little effect of attrition. Nuggets of such friable material as galena and anglesite have been found by the writer in bajada placer gravels; also limonite pseudomorphs after pyrite, which show sharp edges of the cube. The lack of evidence of attrition is due probably to the short distance traveled under stream conditions. Probably a small percentage of the gold is freed during this phase of the movement of gravel. The gradient of these intermont drainage channels is too high to permit lodgment of the finer gravel. When a small amount of gravel is temporarily lodged in one of these channels, the deposit displays most of the characteristics of stream gravel.

As debris reaches the bajada slope a rapid diminution in volume of water due to seepage and an extreme decrease in the grade of channel causes deposition of debris, and either (1) an alluvial fan or (2) a gravel-mantled pediment may be formed. If detritus is supplied to a bajada slope much faster than it can be removed, an alluvial fan is the result. Very few alluvial fans are being formed in the Gila Desert at present but eroded remnants of old fans, some of immense size, exist in scattered localities and witness the lack of stability of basin elevation. If rock debris is supplied to the bajada slope in considerable volume but not in excess of the quantity capable of transferance to the center of the basin by the existing agencies, a gravel-mantled pediment results. The latter is the commonest piedmont topographic expression in the Gila Desert and many bajada placers are related to pediments. Sometimes neither pediment nor fan results and bedrock slopes rapidly away from the foot of the range. At least one bajada placer occurs in such an environment. This situation may represent a planed-off alluvial fan or a buried pediment.

Deposition of Gold

The bulk of the gold that has been released from its matrix on the journey from lode outcrop to bajada slope is deposited on the bajada slope close to the mountain range. The gold is dropped along the contact of the basin fill and bedrock; this is referred to hereafter as the "lag line" and is coincident with the line of contact of bajada gravels lying at a low angle and the rock slopes of the range standing at a high angle. This line is lobate and necessarily parallel to the foot of the mountain range. The line is not fixed in position but moves in the direction of the crest of the range as the tide of detritus lying against the mountain flanks moves upward and toward the mountains, eventually to engulf them.

The heaviest deposition of gold is on bedrock at the lag line, and since the lag line is moving in the direction of the crest of the range, values on bedrock may be distributed over a large area of which the longest dimension is parallel to the foot of the range. Because bulk concentration does not operate as in a river channel, and a certain percentage of the gold is still locked in fragments of matrix, to be partly released by further disintegration on the bajada slope, there is a strong tendency for less gold to reach bedrock and for more to remain erratically distributed throughout the detritus than in the case of stream gravels.

The finer material of bajada gravels is constantly being shifted toward the axis of the basin, by wind, sheet floods and mud flows. Rills are formed on the bajada slope and filled by deposition to form anew. Washes or normally dry water courses with anastomosing and continuously shifting channels move material toward the axis of the basin. All these processes operate with a pediment development, to leave a relatively thin sheet of gravel over a gently sloping rock floor. Concentration of values has been operative to a certain limited extent, since this mantle consists of only a fraction of all the material brought from the hills and contains practically all of the gold. The concentration thus effected does not approach in efficiency the continuous concentration of running water in a confined channel but does much to nullify the heavy dilution of the gold-bearing gravels by barren material.

A certain percentage of the gold detached from the outcrop and transported to the bajada slope remains locked in small fragments of matrix and will not be amenable to placer recovery. Many such fragments have been found in bajada gravels by the writer and when pulverized and washed yielded from one to several colors.

Owing to lowering of the basin level, bajada placers may be dissected by dry washes or arroyos. Where these dry water courses cut the lag line at a high angle, they cut through the short dimension of the placer deposit, and a slight concentration of the values is effected in the channel of the wash. Where the arroyo cuts the lag line at a low angle a proportionally greater quantity of the placer gravels are reworked and the enrichment by concentration in the channel of the arroyo is correspondingly higher. These enriched channels are usually narrow and seldom extend far below the lag line, although in an arroyo cutting the lag line at a low angle and traversing the long dimension of the bajada placer, enrichment may be considerable. These enriched channels were eagerly sought for, and in many cases were exhausted by the early placer miners. The bulk of the bajada placer gravels were generally unattractive to the early miners because of their low tenor and the consequent difficulty of showing a profit with their methods of beneficiation of small quantities with a minimum of water. Not all washes cutting the lag line of bajada placers are auriferous, as with pediment dissection, where an arroyo

may cut the lag line at a high angle and dilute the auriferous gravel so obtained with barren material derived from cutting into the rock floor of the pediment.

If during an interruption, or temporary instability of conditions of balance between erosion and transportation factors, the contact between bajada gravels and rock slopes should pause in its slow migration toward the summit of the range and, more particularly, if the gravel-rock slope contact should temporarily retreat down the pediment toward the basin center, a progressive enrichment due to reworking of the placer gravels along the line of retreat of the edge of the bajada gravel sheet would result.

Comparison of Bajada and Stream Placers

With a detailed consideration of the background of an average bajada placer of arid regions, the salient points of difference between this type and the stream and eluvial placers of more humid regions become increasingly apparent.

The bajada placer is located at the foot of a mountain range, on the bajada slope, at or close to the contact of the bajada debris with the rock slopes of the hills. Its location at the change in degree of slope is a direct function of this change, therefore its location at this contact is directly dependent on the topography. Its position along the line of contact is directly dependent upon the location within the range of the auriferous lodes that furnish the gold. The bajada placer's location may be somewhat conditioned within the limits set by the above by the drainage issuing from the mountains. This is in direct contrast to the stream placer that lies along the main drainage, old or recent, and is thereby directly controlled in location by the main drainage. The gold of some stream placers has traveled far enough from its source so that the location of a stream placer is only remotely affected by the location of the lode outcrops that supplied the gold. Topography, as it is reflected in stream gradient, conditions the location of a stream placer within the limits set by the drainage. The only factor determining the location of an eluvial placer[8] is the location of the outcrop.

Local areal geology in regard to the riffle-forming and gold-catching capacity of bedrock may affect both stream and bajada placers. The bajada placer is related more directly to the local areal geology than the stream placer. The source of bajada placer gold is relatively close at hand and since the lodes constituting the source are closely related to and constitute a part of the areal geology, the bajada placer is related more or less directly to its own geologic setting. The stream placer is not so closely related to its own rock-formational surroundings as the

[8] An eluvial placer is regarded as residual regolith and therefore bears little resemblance to either stream or bajada placers.

gold contained in the stream placer may be a product of an entirely different geological environment. In the special case of ancient channels, a direct relation to local rock formations may have aided in preservation of the placer, as in lava-capped channels.

The stream placer is related to immediate structure only remotely as it affects drainage, except in the special case of ancient and elevated channels. The eluvial placer is related to structure only as it concerns the lode of which the residual debris forms the placer. Bajada placers are more closely related to local structure both as it concerns the lode supplying the gold and also to jointing of local rocks, as in arid regions jointing exerts a control on the angle of slope and the rate of erosion, both of which are reflected in the bajada placer.

Rock decay and weathering are the causes of release of gold to form any type of placer deposit. Erosional processes, however, differ in effectiveness in different regions and the greatest divergence in their operation and result is probably to be measured between aridity and humidity. In bajada placer formation mechanical weathering is the dominant disintegrating force at work on auriferous outcrops and in the reduction of material to free the gold. In most stream placers chemical weathering was probably equally important, or nearly so.

Transportation is an important adjunct to concentration in both stream and bajada placers but is less vitally important in the latter. Transportation of stream gravels in most instances is over a much greater distance than that of bajada gravels, consequently corrasion and attrition were of more importance in reduction of detritus of stream placers and concentration is carried much further by transporting agencies than could be effected under arid conditions.[9]

The characteristics of surficial deposits of bajada placers exhibit considerable divergence from those of stream and eluvial placers. Where overburden exists on bajada placers it is related directly to the adjacent mountain range or to the adjacent basin. In both cases certain definite relationships hold and the relationship of overburden to either basin or range can usually be ascertained by the character of its constituents. If the overburden is related to the range, the thickness of the overburden at any point generally varies directly as the distance from the foot of the range; if related to the basin, the thickness of the overburden at any point usually varies inversely as the distance to the axis of the basin. This is due to migration of the lag line toward the crest of the range

[9] Eluvial placer material represents the zero point in transportation because the material is residual. The stream placer is close to the end point in transportation; beach placers may perhaps be considered the absolute end point. The bajada placer is intermediate between stream and eluvial placers in transportation; its gravels have undergone some transport under unusual conditions and transportation was not of sufficient duration or intensity to have effected much sorting of material.

in one case and to rapid accumulation of bolsa sediments in the other. Bajada placer overburden is usually the same kind of material as the placer proper, a coarse angular aggregate of rock spalls. Barren overburden of a stream placer may be caused by a thorough jigging action by the stream, which concentrates the gold in the lower portion of the gravel mass. Nothing analogous to this takes place in a bajada placer. Changes in elevation and stream gradient may cause overloading of the stream and deposition of overburden material. A bajada placer occurs at a point of extreme change in gradient and loss of water volume, so that overloading and deposition of all but the finest material is usual. This material is further reduced in size by weathering and removed by wind and water agencies, with a lag of gold that produces a placer, so that overburden indicates lack of balance between accumulation and removal, or cessation in the flow of gold. There is a vague similarity of basic cause and result in accumulation of overburden in stream and bajada placers, but processes operating on a bajada placer are conditioned by aridity and the result is therein greatly modified.

The character of the overburden partakes of the character of the auriferous detritus in both placers. In stream placers well rounded pebbles, gravel, sand and even finer material show the effect of attrition and water sorting. In bajada placers, overburden and auriferous gravels are a rough aggregate of rock spalls and fragments, even the finest of which show pronounced angularity. Usually there is a predominance of larger sizes and sorting of material is seldom evident. Stream gravels usually are of regional derivation and represent many rock types, although only the hardest, most erosion-resistant types remain. Bajada gravels are of more local origin and represent few rock types; they may contain both soft and resistant rocks. Homogeneity and lack of jointing operate to preserve the entity of rock fragments in a bajada placer rather than resistance to attrition. Massive tuff may persist as boulders where contiguous granites exist only as small fragments.

The comparison of the parts of the placers that contain values, "pay dirt," shows several factors of economic importance. In bajada placers as in stream placers the bulk of the gold is on or near bedrock, but in bajada placers extreme concentration on bedrock is rare and a higher proportion of the gold remains disseminated throughout the bulk of the gravels than in the stream placers. A stream placer may show several "runs" on bedrock due to meandering of the main channels and runs on bedrock are not uncommon in bajada placers, where they follow the channels of ephemeral water courses crossing the lag line, usually at a low angle, and later buried by the rising edge of the bajada sheet. Runoff channels on this part of the bajada sheet are rapidly shifting in position, so that such runs usually are short and of erratic

tenor and, in general, vary in richness inversely as the lag-line angle of their channels. Stream placers may show more than one auriferous horizon due to deposition of gold on a clay diaphragm or other false bedrock. Cases analogous to this are rare in bajada placers. Bajada placers may show several auriferous horizons but usually this is due to interfingering of bajada gravels with barren basin sediments. A rapid accumulation of sediments in the bolson may cause the bolsa sediments to overlap on the bajada gravels at succeeding stages in their deposition. This overlap gives the effect of several auriferous horizons. Distribution of values in stream placers, although far from uniform, follow certain rules of velocity of flowing water. Bajada placers, because of lack of sorting, lack of confinement in any channel and the release of some of the gold in the placer as well as en route, are apt to exhibit a more erratic distribution of values than stream placers, both horizontally and vertically. Bajada placers usually show an appreciable and even considerable residual enrichment on the surface due to removal of lighter material by wind and sheet floods. This superficial enrichment, unless recognized and discounted, may give rise to serious errors in casual sampling. This kind of enrichment apparently is rare in stream placers but has been encountered by the writer in partly dissected stream terraces that were being eroded under semiarid conditions.

Most of the gold of bajada placers is coarse. It is almost entirely rough and angular and adhering quartz and limonite are common. The average fineness of bajada placer gold for Arizona is about 850, which corresponds closely to the fineness of the stream placer gold of the same and adjacent areas. Theoretically the gold of stream placers of an area should show a greater degree of purity than the gold of bajada placers. The similarity in fineness might be due to enrichment in outcrop before the gold was released. Enrichment, to be effective, must proceed at a more rapid rate than erosion of outcrop, but enrichment having been effected might be arrested, permitting erosion of outcrop and contribution of contained gold to placer deposits.

Conditions Affecting Prospecting and Development

The conditions affecting prospecting and development of bajada placers are mostly adverse. This may not be an unmixed evil, as it has operated to delay the exploration of these placers until gold is at a premium and the larger part of the gold in stream placers has already been won. The factor of greatest moment is lack of surface water for working the gravels. Often potable water is also lacking. Vegetation is negligible in the Sonoran Desert; this is a detriment in that even the simplest timber for operation is lacking and is an advantage in that there is no necessity for clearing minable areas. Prospecting of bajada placers is made difficult by the fact that they represent an irregular and often

ill defined area on the debris-covered flanks of a mountain range. The range of prospecting a stream placer is often delineated clearly by the banks of an old or recent stream channel. Auriferous gravels of a bajada slope lack this clarity of expression. The question of tenor, quantity and position of the auriferous terrain of a bajada placer is not as easily solved by the drill as in a stream placer, as it presents a geologic problem foreign to stream placers. Since availability of water is of paramount importance, the geologic problem of the placer involves a detailed scrutiny of the water resources of the area. The geologic-economic problem of a bajada placer is amenable to solution through study of the environment and method of formation of the placer, since its characteristics are largely a reflection of these features.

The total extraction from bajada placers has been accomplished through small-scale hand methods; often by dry washers of the hand blower type. Only the richer portions of these placers could be mined by this method and these are exhausted.

It is the writer's opinion that any large-scale development of bajada or other types of dry placers will not be attended by any revolutionary advances in methods of dry washing but is contingent upon an intelligent development and application of the subsurface water resources of the region.

DISCUSSION

(*John Wellington Finch presiding*)

E. D. Wilson,* Tucson, Ariz. (written discussion).—In announcing his independent observation that many placers are related to pediments, Mr. Webber was unaware that this relation had been previously described[10]. Transportation, concentration, and deposition of placer material on pediments (and "bajadas") are but part of the sedimentation process that, as Bryan has shown[11], is largely the work of running water. Although this work is conditioned by aridity, the concentrating factor of the running water should not be minimized. Numerous accumulations of black sand in local channels on pediments point to rather extensive concentration of heavy minerals. I believe that Mr. Webber has overestimated aridity, wind work, and sheet-flood action on the pediments, as contrasted with the work of water in rills and channels there. The rich placers discovered since 1930 near Quartzsite, in western Arizona, occur on a concealed pediment. Their distribution[12] clearly indicates deposition in channels that trend perpendicular to the face of the mountain range, rather than along Mr. Webber's "lag line." His assertion that pyritic replacement deposits, particularly, contribute a certain quota of the placer gold is subject to the objection

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* Geologist, Arizona Bureau of Mines.

[10] E. D. Wilson: Arizona Gold Placers (Fourth Edition, Revised). Univ. of Ariz., Ariz. Bureau of Mines *Bull.* 135 (Aug. 15, 1933) 12–83.

[11] K. Bryan: The Papago Country, Arizona. U. S. Geol. Survey *Water Supply Paper* 499 (1925) 93–101.

[12] Reference of footnote 10, 29–30.

that pyritic deposits in Arizona have formed commercial placers only where free gold is present in the unoxidized zone.

Mr. Webber doubts that a commercial bajada placer would result from the erosion of numerous auriferous veinlets or stringers, unless they were closely spaced and very rich. He asserts that limitation in area of origin and degree of concentration "make it necessary to postulate one or several lodes of at least moderate size and tenor and probably containing oreshoots of unusual richness." Contrary testimony is offered by southwestern Arizona's largest and richest placers, none of which are traceable to known lodes of even moderate size and tenor. Ten ¼-in. stringers with an average of 0.50 oz. of gold per ton through a length of 500 ft. and a depth of 300 ft. could yield $24,000 worth of placer gold (with gold at $20.67 per ounce), while a million-dollar placer (with same gold value) could result from the erosion of 416 stringer bodies of that same very modest width, length, depth, and tenor, provided perfect concentration obtained. They might easily occur within an area of a few square miles and be amenable to placer-forming erosion and sedimentation under the most arid conditions in Arizona.

Government Surveys and the Mining Industry from the Viewpoint of the Mining Geologist

By Reno H. Sales,* Member A.I.M.E.

(New York Meeting, February, 1934)

The present-day application of geological knowledge to mine operations owes much to Survey activities. Early publications covering developed deposits at Comstock and Eureka in Nevada, and Leadville in Colorado, aroused great interest in mine geology among mine owners and operators. In later years personal contacts between Survey geologists, notably Lindgren, Spurr, Emmons, Weed, and Ransome, to name only a few, and mine managers, mine superintendents and mine foremen, brought directly home the importance of geological mapping and study in connection with mine operations.

However, the Survey had recognized from the beginning that it was not practicable, either from the viewpoint of cost or policy, to supply direct help to the miner. The situation was met by many large mining companies through the organization of geological departments to deal with problems of geology which concerned not alone the every-day mine operation but also the life expectancy of the ore deposit. The mine owner therefore looked to the mine geologist to apply the "laws of ore deposition" in estimating the future of his mine. The examination of outside properties also became a duty of the company geologist where replacements were needed or where expansion of operations was contemplated. And finally, out of this situation there developed the independent consulting geologist, specializing in geological examinations of prospects, mines, and mining districts, whose duties included the highly important but often difficult task of appraising ore reserves and ore possibilities.

Thus, while it may be considered by many that the work of the mine geologist overlaps that of the Survey geologist, their respective fields of endeavor are not in conflict. The appearance of the mine geologist has lessened in no manner the need of intensive field and research work by the Geological Survey and related organizations.

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Geological Survey Objectives

Concern has been expressed[1] recently by one or more members of the Survey as to how the activities of that organization fitted into the scheme of things under the greatly changed conditions within the mining industry with respect to geological work. It seems pertinent to ask whether the present order demands a modification of the early policies and objectives of the Survey as set forth some 30 years ago by C. D. Walcott, then Director of the United States Geological Survey, and later by S. F. Emmons, in charge of investigations of metalliferous deposits.

In 1900, at the Washington Meeting of the American Institute of Mining Engineers, Walcott said:[2]

> The general principle upon which the survey has been doing its economic mining work is, that it should endeavor to accomplish for the mining industry, as a whole, what the individual mining engineer or mine owner cannot succeed by his unaided exertions in doing; that it should not undertake to do what could be done as well, if not better, by individual exertion; that it should not interfere, either favorably or unfavorably with the private business of individuals or corporations, or enter into competition in their legitimate occupations with professional men, such as mining engineers, etc.

Two years later, Emmons wrote:[3]

> The fundamental principle of the method of work adopted has been that its primary object is to endeavor to determine the general laws which govern the formation of ore deposits, the immediate aid that may be derived by any mine owner or group of mine owners in working their private property being of secondary consideration, though, of course, a result to be aimed at.
>
> In carrying out the principle outlined above as governing the mining work of the Survey, inasmuch as it has been manifestly impossible to study all mining districts at once, those have been first chosen in which the extent of underground workings in actual operation and the peculiarities of geological structure promised to make us most intimately acquainted with all the varied phenomena of ore deposits, and hence to yield the most important scientific results, that these results should prove of immediate practical importance to those engaged in working the particular mine examined, while a most desirable object was considered of relatively secondary importance and one to the accomplishment of which no jot of scientific accuracy should be sacrificed.

Obviously, Walcott's statement covers the broader aspects of Survey work, while Emmons had in mind activities related to the strictly metalliferous deposits. Present discussion is confined chiefly to deposits of precious and nonferrous metals.

Have the Original Purposes of the Survey Been Fulfilled?

In the appraisal of work accomplished in the past by the Survey from the viewpoint of the company geologist, or the consulting geologist, it is essential that the objectives outlined by Walcott and Emmons be kept

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[1] D. F. Hewett, private communication.

[2] *Trans.* A.I.M.E. (1900) **30**, 3.

[3] *Eng. & Min. Jnl.* (1902) **74**, 43.

clearly in mind. Differences of opinion will exist, no doubt, among mining geologists as to how well the Survey has succeeded in carrying out these objectives. With respect to the examination and study of mines and mining districts, but few, if any, will dissent from the opinion that the Survey has done a good job. Practically every district of importance has been covered by competent geologists. Maps and reports have been issued, covering in detail the geology of the ore deposits under consideration. In many of the more thoroughly developed districts elaborate reports have appeared with full and comprehensive discussions of geologic structures, ores and ore genesis. These publications set a uniformly high standard in geological work, and their great value as aids to the prospector, miner, and operator are recognized.

Notwithstanding the declaration by Emmons that the "Primary object is to endeavor to determine the general laws which govern the formation of ore deposits," there has been, in the more recent years, a decided drift of Survey activities to the examination of regions of new discoveries and partly developed areas, with less attention being paid to well developed districts. No objection will be raised to Survey activities in frontier regions. These constitute a very important part of the present-day program of mineral development. There has been no falling off in the high quality of results produced. Such work is most helpful, highly desirable, and popular demand requires it. Whether there has been in the past, or is now, a proper balance in Survey effort covering the scientific side, on the one hand, and what might be termed the more practical help toward the development of mineral resources, on the other, is a question deserving the most careful investigation and study by those in charge at Washington.

In the light of the expressed primary objectives with respect to metalliferous deposits, a search among Survey publications for periodical records or reviews recording advances or discoveries made relative to the laws of ore deposition will be disappointing. With the possible exception of *Bulletins* 529 and 625, by W. H. Emmons, issued in 1913 and 1917, respectively, dealing exhaustively with secondary enrichment processes, nothing has been published summarizing or correlating, from time to time, the vast amount of information collected in the field and laboratories by Survey men employed on work dealing with the problem of ore genesis.

From this general observation it should not be inferred that the Survey has failed in the past to direct its principal energies toward the accomplishment of the main objectives. One need but call attention to the vast number of valuable papers on the subject appearing in technical journals, transactions of engineering societies, and allied publications. Whether the Survey preferred this method of disseminating the more generalized results of its work on the problem of ore deposition, or whether it was a course of action necessitated through the lack of pub-

lishing facilities or legislative appropriations, is not clear at the moment. The writer's belief and opinion is that the Survey should have taken the lead from the beginning and assumed the responsibility of keeping the mining industry informed, through its own publications, of progress made. An annual review, such as formerly appeared in the well-known *Mineral Industry*, yet more comprehensive, summarizing and correlating facts and theories on ore deposition, would have greatly stimulated thought and investigation among those engaged in mining enterprises. Furthermore, such a compilation would have formed a sound basis and guide for each succeeding year's activities of Survey men engaged in work having to do with this particular subject. On the basis of free distribution, in vogue until recently, the results of Survey efforts would have had a wide dissemination among those actively engaged in mine operations, reaching a very large number who have not had ready access to the output of technical societies.

Present Activities of the Survey and Needs of the Mining Industry

Unquestionably, the needs and requirements of the mining industry have changed during the past 20 years. The Survey must now be considered as having at least two important objectives, namely:

1. The science of ore deposits, or the determination of the general laws governing ore deposition.

2. Extending aid of a more practical nature to the prospector and miner in unprospected areas, in newly discovered mineral localities, and in promising districts during early stages of development.

From the point of view of public relations, and the miner, these two objectives vitally concern the economic development and conservation of the nation's mineral resources. A discussion of these from the viewpoint of the mining geologist is in order.

Science of Ore Deposits

Study of Major Districts

It seems unnecessary to set out in detail the reasons why a knowledge of the progress being made in the study of ore deposits is of interest and value to the mining geologist, the mining company geologists in particular, and to the mining industry. It must be realized, however, that it is not within the range of possibility that a complete and full knowledge of the laws governing ore deposition will enable even those most qualified to appraise correctly the unseen orebody as to size and metal content. In this connection the industry recognizes the usefulness and value of existing Survey publications dealing with ore deposits and problems of ore deposition in the more highly developed districts.

All will agree with Emmons' observation that in general the most fruitful sources of information relating to the problems of ore deposition are to be found in the active, more maturely developed districts. Therefore, earlier Survey reports should be supplemented by re-examinations of sufficient frequency to keep pace with significant geological developments. In the light of newest discoveries in the problems of ore deposits, such examinations would be helpful to the student of ore deposition, to the practical mine geologist who holds as one of his chief objectives the prolongation of the life of the mine, and to those responsible for conserving the nation's mineral resources.

In recent years the greater part of our nonferrous metal production, excepting gold and possibly some of the rare metals, has been won from a relatively small number of districts. Consequently, many who prospect for ore look with favor upon the undeveloped areas of producing districts, for the reason that the presence of geological conditions favorable to the formation of commercial orebodies has been demonstrated. Intensive geological study and research is greatly needed therefore in proved areas, not alone for the purpose of prolonging the life of the particular district under consideration to the greatest extent possible, but as an aid to prospecting in geologically similar areas having mineral possibilities.

These observations and conclusions apply with equal force to abandoned or partly abandoned mines having records of substantial metal production, but which may become accessible for study during recurring periods of activity. The Comstock and Eureka districts in Nevada are outstanding examples of this class. Both were subjects of elaborate reports, published in the years 1882 and 1884, respectively.[4] But, notwithstanding the large production of gold and silver from the Comstock lode, after the year 1882, and the accessibility of a wealth of geological facts of absorbing interest to the student of ore deposition, and to the mine owner of that district, no re-examination was ever made. The same criticism applies to Eureka, and to a large proportion of the 20 or more maturely developed mining districts now in active operation.

The "determination of the laws of ore deposition" always has been, and should remain, one of the most important objectives of Survey effort, and the application of geological knowledge gained through Survey activities is the obligation of private enterprise. But that the Survey has not followed the proper course with respect to keeping the mining industry informed on geological developments vital to the study of ore genesis is evident from the scarcity of publications on that subject, and the lack of interest displayed toward major districts.

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[4] G. F. Becker: Geology of the Comstock Lode and the Washoe District. U. S. Geol. Survey *Mon.* 3 (1882).

J. S. Curtis: Silver-lead Deposits of Eureka, Nevada. U. S. Geol. Survey *Mon.* 7 (1884).

Through cooperation, examination, and study of developed areas, four worth-while objectives are, to a varying degree, possible of accomplishment; namely, (1) definite and orderly progress in the solution of the problems of ore deposition, (2) increasing ore reserves and affording valuable aid to the miner engaged in the development of similar ores elsewhere, (3) rejuvenation of abandoned or partly abandoned districts, and (4) correction of previous errors made in the identification and classification of rocks, formations, faults, and vein structures, and in the more serious matters pertaining to theories of ore deposition; a most important objective when it is realized that Geological Survey work furnishes the broader geological background, not only for the more specialized work of the mining geologist but also for those of the Survey who are engaged in the investigation and study of mineral deposits.

As a part of a program to attain these objectives the following suggestions are offered:

1. Maintenance of an orderly record, published annually or at such intervals as may be deemed advisable, designed to present a brief up-to-date summary of the general trend of thought and study relating to the laws of ore deposition. Such a publication should emphasize the work done by the Survey and the part being played by it, through field and laboratory study, in the common effort to reach the important objectives originally set as its goal.

2. Stimulation of interest in abandoned or partly abandoned major districts by re-examination and study in the light of current knowledge and thought on the subject of ore deposition, and by bringing essential geological information to date. New geological maps or reissues of earlier maps, accompanied by brief reports or abstracts of out-of-print reports, would be most welcome to the mining geologist and the mining industry. Some of the country's largest districts, formerly producing great wealth, now are down or only mildly active, with no Survey records other than those made in the early days of discovery and development. Goldfield, Tonopah, Eureka, and Comstock, in Nevada, and Mercur in Utah, are well-known examples.

3. Investigation and study, in cooperation with local mining-company geologists, of problems of ore deposition not necessarily included, for reasons too numerous to mention, in the daily calendar of activities of the local staff. Among the most important problems for study, common to large fissure-vein deposits such as are found in the Butte and Coeur d'Alene districts, are the following:

(*a*) Relation of the ore deposits to the successive periods of igneous activity.

(*b*) Significance of rock alteration within and adjacent to veins and fissures.

(*c*) Mineral zoning.

(*d*) Paragenesis of minerals and overlapping mineral zones.

(*e*) Mechanics of fissuring, including post-mineral faulting and a study of the behavior of fissures and fissure systems under increasing pressure at depths.

(*f*) Genetic relation and classification compared to other districts.

To these should be added the unsolved problems encountered in areas geologically different from the districts mentioned. Two of these, worthy of serious study, are met with frequently: (1) origin and manner of introduction of the large sulfide masses of Bingham, Bisbee, United Verde, and Ducktown, and coupled with this, (2) the reason for the commonly noted succession of sulfide minerals in this type of deposit, beginning generally with iron pyrite and ending with sulfides high in copper, lead, and zinc.

The phenomena of alteration, slumping, dolomitization, and garnetization, so frequently found associated with ores occurring in limestone, are deserving of careful and thorough study. Each type of deposit has its own problems. However, it is the writer's opinion that the study of a single deposit or district may yield but a slight contribution to the general problem. Substantial progress will be made by carefully comparing and correlating significant facts learned in laboratory and field, concerning ores and ore deposits exhibiting similar characteristics as to mineral composition and geologic setting.

Survey geologists many years ago realized the need of broad generalizations. *Professional Papers* 68 and 111, entitled respectively "The Ore Deposits of New Mexico" and "The Ore Deposits of Utah," both long out of print, may be cited as notable contributions resulting from a well thought out plan of assembling and correlating geological information. With no reflection upon the value and usefulness of publications of this type, it is the opinion of the writer that from the point of view of the student of fundamental problems involved in the science of ore deposits, broad considerations of "geologic" units rather than "geographic" units, are more helpful. This point may be illustrated by what has happened in Montana. A number of Survey publications have been issued covering mining districts within or bordering the Boulder batholith. The ore deposits of these districts are believed to be related primarily to the batholithic intrusion. The logical plan of action, from the point of view of the scientist, prospector, or mining geologist, would have been to make a study of the batholith and related ore deposits, along the general line of attack followed by Billingsley and Grimes.[5]

Furthermore, such a study could be made to serve another useful purpose; namely, that of tying in and correlating the work of the economic geologist with that of the scientists working on the broader problems of

[5] P. Billingsley and J. A. Grimes: Ore Deposits of the Boulder Batholith of Montana. *Trans.* A.I.M.E. (1918) **58**, 284–361.

geology. For example, cooperative field work between Survey geologists working on the problems of ore deposition and the geologist of the Division of Geology of the National Research Council, which is making an intensive study of batholiths, would be a desirable and logical procedure.

It should be kept in mind that the mining-company geologist maintains primarily a record of the effects of geologic processes, but no record, necessarily, of his knowledge, or of his theories of the processes involved. Nevertheless, many problems of ore genesis receive most serious consideration, in so far as time and the usual limited laboratory facilities permit, and to the extent that such study is deemed to be of value and assistance to the mine operation. Naturally, the amount and intensity of thought given by the mine geologist to the subject of ore deposition varies greatly in different districts, depending, to some extent, upon the nature and complexity of the problems presented.

Undoubtedly there is a certain amount of overlapping inherent in the duties of Survey geologists and mining geologists, particularly at mines where mine geological departments are in existence. But the situation Walcott had in mind is exactly the situation today; namely, the Survey "should endeavor to accomplish for the mining industry, as a whole, what the individual mining engineer or mine owner cannot succeed by his unaided exertions in doing," and "it should not undertake to do what could be done as well, if not better, by individual exertion," and further, "it should not interfere, either favorably or unfavorably with the private business of individuals or corporations." The fear expressed more recently by Survey members that its field of operation is being invaded by mine geologists is without foundation. The mine geologist performs the service of applying geological knowledge, a very large part of which has come to light through Survey activities, to mine operations, thus covering the field specifically exempted by Walcott and Emmons from the duties of Survey geologists.

Hewett[6] recognizes the impracticability of Survey geologists mapping our large western mines, because of the great extent of underground workings and inaccessibility of a large part of them. Fortunately, owing to the foresight of the mine operator, the geologist made his appearance early enough in most of the large districts to preserve geological records of vital interest to the student of ore deposition. Thus, in one respect at least, the mine geologist has been of service to science.

Where a re-examination of a district is undertaken by the Survey, the mine geological record serves two purposes: (1) supplying valuable geological information inaccessible to the examining geologist, and (2) making a re-study of the district possible within a reasonable period of time. As an example of high accomplishment where there was coopera-

[6] D. F. Hewett: private communication.

tion between local and Survey geologists, *Professional Paper* 144, dealing with the Lake Superior copper deposits, is notable. This work, a most worthy contribution written in the light of modern developments in the science of ore deposition, is a valuable addition to geological knowledge. It contains a wealth of facts on geologic structure and on problems of ore deposition, useful not alone to the student of ore deposition but to those who mine and search for ore in the Lake Superior copper district and elsewhere.

But what is to be said of the 56-year interval between R. D. Irving's Monograph on the Copper-bearing Rocks of Lake Superior and *Professional Paper* 144, by Butler and his collaborators? How much information of scientific interest was lost to Butler because of worked-out orebodies marked only by inaccessible mine workings?

When should the industry be apprised of advances made in the science of ore deposits in order that the information may be of service? Manifestly, as near as possible to the beginning of ore development in a district, not near the end, or after apparent death, in hopes of revival where the field of study and observation underground has become limited to crosscuts, prospect drifts, or other openings where no commercial ore was found, or to surfaces dotted with caved and inaccessible pits, shafts, adits and stopes. Every major district should at all times be a live subject for the Survey, and, as Billingsley expressed it, "not one of them should be embalmed in a monograph twenty or even five years old."

And what of the problem of training for technical and field staffs of the Survey? In view of the common sense advisability of continuing the drive for the main objective, namely, "the determination of the laws of ore deposition," how can the Survey build up an organization equal to the task if the members are not afforded the opportunity of personally familiarizing themselves with developments in major districts, where, in the words of Emmons, "the extent of underground workings in actual operation and the peculiarities of geological structure" promise "to make us most intimately acquainted with all the varied phenomena of ore deposits, hence to yield the most important scientific results?"

Survey Work in New Districts

Recognized Value

One of the first acts of a mining geologist, before starting on a mine examination trip to a locality in the United States with which he is not familiar, is to find out what has been published by the Geological Survey covering that particular area. As a rule, if a district has been the scene of ordinary mine development, something will be found, either a topographic map, geologic folio, or sufficient descriptive matter in a bulletin or other publication to be of immediate assistance. The above is cited

as proof of the recognized value and usefulness of Survey publications. The field geologist and mining engineer would be tremendously handicapped without them.

Earlier in this paper reference was made to the drift of Survey activities from major districts to new undeveloped areas, mushroom camps and distant regions, such as Alaska, where gold and copper discoveries attracted prospectors in great numbers but where transportation and operating difficulties were very great. The Survey officials at once recognized the needs of these pioneers on the geography, topography and geology of unmapped or little known areas where courageous efforts were being made to build up new mining enterprises. In addition, heavy calls were made by mining associations and civic clubs for service in districts partly abandoned by the first wave of prospectors.

Criticisms of Survey Work

The Geological Survey and its activities, briefly referred to in the immediately preceding paragraphs, have been the objects of criticism, much of which is groundless, in the opinion of mining geologists in general. Adverse criticisms most commonly heard, and believed by the writer to be warranted to some degree, may be summarized as follows:

1. Examinations of discoveries in new territory are too long delayed, and follow-up examinations of subsequent development are too infrequent.

2. Too much time elapses between field examination work and date of publication.

3. There is unsatisfactory distribution of publications, including maps and statistical information.

4. Publication issues are much too small on important individual mines or districts.

5. There are no reissues in full or in abstract form, of out-of-print reports, and no separate issues of geological maps that are made to accompany reports.

6. Overlapping of activities of national and state geological surveys are not satisfactory. There are two principal objections to this: (1) it makes information less accessible than when accumulated under one organization and under one directing head, and (2) it enables state and national organizations to dodge responsibility.

Survey publications should be issued promptly. There has been far too much delay in the past. Where the importance of the subject demands, a preliminary report with maps is advisable, leaving final complete report to follow full study of facts. These remarks are equally applicable to reports and publications covering developed districts.

If it be worth the time, effort and expense to collect geological and useful data for the prospector and miner, it is worth the effort and expense required to get it into his hands at the earliest possible date. A

speeding up of publications covering results of field and laboratory work is necessary if this most persistent criticism of the Survey is to be silenced.

The methods employed for distributing Survey maps and publications are far from being efficient and satisfactory. Publications generally carry the following important announcement: "Additional copies of this Publication may be procured from the Superintendent of Documents, U. S. Government Printing Office, Washington, D. C." But what of the prospector, miner, mining geologist, or anyone interested, getting that crisp bit of information concerning publications while in the field around Juneau, Seward, or Nome, Alaska, or even in the western part of the United States? Taking Alaska for example, surely the mineral production of that Territory, amounting to a yearly round figure average of $21,500,000 since 1905, and a total of $629,313,000 to the end of 1930, of which $389,317,000 was gold, justifies the expense necessary to maintain at all times a full supply of Survey maps and publications on Alaska, both for library reference purposes and for sale, in a number of places in that vast territory where transportation facilities are slow and difficult. Apparently there is not a locality in Alaska, or in the United States other than Washington, D. C., where Survey publications and maps of local interest can be purchased. If there be such places, the fact should appear in each bulletin and in the regular lists of publications.

Whether the issue of Survey publications such as Professional Papers, Bulletins, and maps is too small is a debatable question. At this stage in its long period of existence, it is reasonable that experience would dictate the number of copies of a publication needed to supply public demand. It is true that hundreds of Survey publications, including Monographs, Professional Papers and Bulletins, forming a very large proportion of the total number issued, are out of print and unobtainable. If an "out-of-print" sign signifies anything, it means that the public demanded more copies than were printed. The recent issue of a pamphlet entitled "A List of Publications of the United States Geological Survey," with its hundreds of asterisks indicating "out-of-print," tells a story.

The writer is not unmindful of the difficulties involved in estimating public requirements in advance of publications, as well as the inadvisability of having unsold stocks occupying valuable and perhaps much needed space in Government buildings in Washington. With respect to surplus stocks, however, the situation might be saved by maintaining unsold publications of local interest at convenient points for distribution.

Geological maps made to accompany reports should be issued separately as well as with the final report. Full reports are often expensive to the purchaser, and from experience it may be expected that they soon will be out of print, and with them will go useful maps. Surely the need

of a change in policy has been demonstrated. In this respect, as well as in many others, the Canadian Geological Survey has shown the way.

The mining geologist's greatest needs in examination work are contour and geological maps. For newly discovered districts, prompt publication of preliminary or reconnaissance geological sheets is most helpful, not only to the examining geologist but to the mining industry and the public as a whole.

The Survey has made the mistake from the beginning of not striking off extra copies of geological maps made to accompany Monographs, Professional Papers, Bulletins, and Geologic Folios. Here again, if it is worth the effort and expense necessary to prepare and publish large and expensive treatises, the small additional expense of printing separates of the geological sheets, which form the groundwork of the reports, is justified.

In general, with respect to new fields of exploration, our Government might well copy methods used in Canada for aiding the prospector, miner and mine operator on so-called mineral frontiers. The length of frontier in the United States has dwindled to some degree in recent years, while in Canada it has greatly expanded. Thus, by comparison, wherein Canada looks forward to increasing mineral production from discoveries in unexplored territory, the United States must look more and more to discoveries and extensions within developed or partly developed districts. Logically, it follows, from what has been said earlier in this paper about Survey activities in relation to old and new districts, that in the United States the problems relating to ore deposition transcend in importance those having to do with new or unexplored territory.

This does not mean to imply a relaxation of effort along our mineral frontiers such as Alaska, and in the less known regions in western United States, but instead, in view of future metal needs, an intensification of effort modeled to a large degree in its practical application after Canadian practice.

Preservation of Mine Records

The Government has been lax in maintaining records of underground work in mines. The mining regions of the United States are dotted with mines and mining districts concerning which no accurate geological or other underground maps are available. In most cases the operators left no data on the ores, as to assay, mineral composition, or physical character. Rarely did they keep records of the flow of mine water. This situation grows steadily worse by reason of the disappearance, through one cause or another, of such records as have been in existence. This unfortunate condition was never more effectively brought to public attention than it has been during recent months in the scramble for gold properties.

Steps should have been taken years ago to remedy this situation, but it is not too late to start now. Since the most important information to be preserved is geological or relates to metal contents, such work properly belongs to the Geological Survey. The Government should go no further than to require that before abandonment accurate geological and assay maps, together with other useful data, be placed for safe keeping in the confidential files of the Geological Survey, subject to the order of the mine owner, his successors or assigns. Such information might become public property if, and when, the property reverted to the state or Government.

It is not intended, however, to do more here than to invite attention to an unfortunate condition within the mining industry. The scope of future Survey activities should be enlarged to include that of securing more comprehensive records of mines and prospects. Let it be recorded, however, that all mine operations are not without responsibility in the matter of maintaining proper mine and geological records, not only for self-preservation but as a means of helpful cooperation with the Government to achieve a common purpose.

Looking to the Future

The position of our mining industry in relation to wealth produced, and number of people employed, is an extremely important one. Of vital moment also is the factor of metal supply in time of war. Prolonging the life of this most important and essential industry, therefore, becomes a matter of national concern. The bugbear of overproduction and excess productive capacity in our mining industry, of which so much has been heard in the past four years, should not be interpreted as proof that there are inexhaustible reserves, within the United States and its territorial possessions, of oil, ores of iron, copper, zinc, lead or other useful metals. The facts are quite to the contrary. However, that there are undiscovered mineral deposits in the United States of great value, no one will deny. To make these resources available, every reasonable effort must be put forth to reduce as far as possible the financial risks involved.

The fact must be recognized that the easily found ore deposits of commercial grade are either worked out or they are in the process of exploitation. Many known deposits of low-grade ore await improvements in mining and metallurgical methods. In the future, increasingly greater risks must be assumed by capital in the search for ore, even where prospecting operations are based upon sound geological theory. Thousands of mining risks have been taken in recent years. Many were successful, but by reason of the fact that it has been wise to try out the best risks first, the field is gradually narrowing to a collection of prospects too unattractive to justify the expenditure of capital or human effort under conditions of average metal prices.

The Government early recognized its obligation to the mining industry by the formation and maintenance of the Geological Survey, and through that organization invaluable aid has been extended in the past. Because of increasing difficulties in maintaining ore reserves, it should be the policy of the Survey to work unceasingly to establish sound geological principles for the guidance of human effort in the search for useful metals, and results should be made available with as little delay as possible. The Government should provide funds upon a much more liberal scale than in the past, to enable the Survey to perform this useful and much needed service.

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[For discussion of this paper, see page 452.]

The United States Geological Survey's Point of View on Relations between Surveys and the Mining Industry*

By G. F. Loughlin† (Member A.I.M.E.) and Members of Its Metals Section

(New York Meeting, February, 1934)

Nearly 55 years have elapsed since the U. S. Geological Survey was organized. During this period the mineral industries have grown from infancy or early childhood to well developed maturity, and some mining industries appear to be declining. Decline in mining is even more conspicuous in certain districts, or even states, than in any mining industry as a whole, and discoveries or developments of important new districts have been very few in recent years. Our reserves of most metals and nonmetals are adequate for many years of normal production, subject to changes in rate of exploitation that may be caused by foreign competition and by changes in technology and market conditions; but the declining production of many districts and the scarcity of important new discoveries to compensate for them is cause for some apprehension. It is likely that future production will depend to a considerable extent on deep exploration and on the thorough examination of places in and adjoining existing districts where significant outcrops are lacking and only apparently insignificant geologic features offer encouraging clues—more so than on the discovery of entirely new districts. Even the possible discovery of new districts, which have escaped the intensive search by the nontechnical prospector, must be dependent on geologic information. There is therefore no need for argument as to the value of geology to the mining industry; and the need of continuing to advance the science.

The U. S. Geological Survey's past contributions to mining geology, as expressed in its official reports and other publications, are recognized by Ransome in his historical review of mining geology in the Lindgren volume.[1] These contributions have helped to form the basis of modern mining geology, which has grown rapidly in the last 25 years. This growth has witnessed the organization and maintenance of geologic staffs by mining companies in several districts, and their detailed work, together with the fact that nearly all of the larger mining districts have

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[1] Ore Deposits of the Western States (Lindgren Volume). A.I.M.E., 1933.

been reported on at least once by the U. S. Geological Survey, raises a question as to the part the Survey is to play in the future. The present miscellaneous demands on the Survey's personnel are more than sufficient to keep it busy, subject, of course, to financial support, and no radical change in its general program seems called for at present; nevertheless, a consideration of its fields of usefulness to the mining industry in the light of changing conditions should be mutually beneficial. These fields really include those of all branches of the Federal Survey, but, as the discussion has been proposed by the Committee on Mining Geology of the Institute, only the activities of the Metals Section of the Survey's Geologic Branch will be reviewed here. These activities may be considered under the following headings: reconnaissance, detailed regional study, study of small districts, re-study of large districts, cooperative programs with Federal, state, municipal, and other public institutions, relations with company and private geologists, topical investigations, and the furnishing of miscellaneous information on the mineral industries requested by Federal and other government organizations and by private organizations and individuals.

Reconnaissance.—Several reconnaissance reports have been published by the Survey, though relatively few in recent years, but even today there are large areas in the western states on which reconnaissance information is in demand. Such information is of value, especially as a basis for more deliberate work, but it is so easy for reconnaissance work to give erroneous impressions that it may well be questioned whether it would not be better to devote the same amount of time and money to a more thorough study of smaller areas, with the hope that the work eventually may be extended until the entire region that needs attention has been covered adequately. Areal work that used to be called detailed—for example, the mapping of a 15-minute or even a 30-minute quadrangle within a season of 3 or 4 months—is likely to be of only reconnaissance value today, and to serve as an adequate basis for practical conclusions it should be re-examined with sufficient time for a thorough study of the critical problems.

Detailed Regional Studies.—Such areal work with time allowed for more thorough study of critical problems becomes a detailed regional study, the results of which are essential to a good understanding of local conditions in mining districts. It is a common experience of Survey geologists that, after covering a mining district in detail, they find that they need to study the surrounding region with the hope of verifying tentative conclusions or of finding clues to questions that could not be answered by intensive study within the district. Regional studies obviously take time, but partial results can be published as the work progresses. There are so many regions on which such information is needed that progress in their study may seem discouragingly slow, but

slow progress is better than none. It is very unlikely that any private organization would undertake these regional studies, whether reconnaissance or detailed. State organizations may care for regional work within their states, but, as regional problems have no respect for political boundaries, the Federal Survey, both because of its national scope, and its larger and more diversified personnel, seems to be the appropriate organization to study them, focusing its findings so far as possible on the economic phases of the problem.

Study of Small Districts.—The satisfactory study of small, or only slightly developed districts involves difficulties, such as lack of basic regional information and the necessity of interpreting conditions on a minimum of available local evidence. The geologist who has had an opportunity to make thorough studies of several large districts obviously has a better background for the interpretation of conditions in small districts and for the coordination of them with such regional information as is available. It would be consistent, therefore, to assign only the older geologists to the study of the smaller outlying and isolated districts, while the younger men are gaining experience first as assistants to older men and later as party chiefs in the larger districts; but the small number of older men and the many different calls for their services render the systematic adoption of such a plan impractical, and the best arrangement under existing circumstances seems to be the assignment of the available men, whether young or old, to projects as they arise, with as much regard for personal qualifications as conditions permit and with as much supervision as possible. The same difficulty may apply to geologists in private employ, with the added circumstance that their examinations in small districts may be confined to one or two properties without the time to make a comprehensive study of the district as a whole. Such comprehensive studies, therefore, which are essential to a well founded appraisal of properties in the district, fall to the Government surveys.

Resurveys of Large Districts.—Most of the large districts, as already stated, have been reported on at least once by the United States Geogical Survey, and the reports have served as starting points for private and company geologists who have worked in those districts. A few large districts have been re-studied by the Survey, either on its own initiative or at the request of mine operators or state organizations, and the results of the new work show the value of periodic re-surveys of rapidly growing and highly productive districts. These re-surveys generally reflect credit on the earlier workers, but emphasize the greater complexity of geologic conditions than were at first realized and also the progress that the science of mining geology has made since the days of the first survey. They also supply new starting points for those doing intensive work. Re-surveys of important districts also preserve impor-

tant information which would otherwise be lost when old workings become inaccessible.

The vast amount of data available in a well developed district requires a much longer time for a thorough re-survey than for the original survey, and a correspondingly longer time for the preparation of the new report, which should present all available facts in well coordinated form and interpretations of the facts, with due regard to the development of geologic science but focused so far as possible upon directly practical problems. The criticism has been made that the Survey's reports on mining districts, whether based on original studies or re-studies, have left too great a gap between the point where the geologist stops and the point where the mining engineer would like to begin. This gap may be bridged by the consulting or company geologist if one is available and if he is authorized to extend his investigations sufficiently. Too often however the areal scope of his work is limited by property lines and an effort is now made by the Survey geologists to bridge the gap themselves as far as possible. Their practical suggestions refer mainly to the district as a whole and application to the problems of individual mines remains for those in private employ.

This attempt to bridge the gap between geology and engineering may seem risky to those of conservative tendencies. It is true that if one refrains from making suggestions he is less likely to make mistakes, but if he has made a thorough study and has correctly observed and assembled the facts, he should have a better basis for making suggestions than anyone else and should have the courage to make them. Suggestions in mining geology should obviously be subjected to critical consideration by those who do the mining or by their consultants, but even a rejected suggestion is more helpful than no suggestion at all, and a suggestion that fails to yield results is no worse if made by a Survey geologist than by a private geologist or a mining engineer. Such failures are due either to the insufficiency of available facts or to the incorrect interpretation of them, but they do not destroy the value of thoroughly presented facts that will always be available for further interpretation whether or not they are supplemented by more facts.

The insufficiency of facts again emphasizes the importance of re-surveys that will tend to correct this insufficiency. This viewpoint has not been unanimously shared by mine operators or even, perhaps, by mining engineers. Some informal inquiries made a few years ago regarding the possible value of re-studies of certain of our leading mining districts by the Survey brought only a lukewarm response. The general feeling of those asked was that more geologic information on any of these districts as a whole would not be worth while, and some suggested that the Survey devote its energies to regions that had never been studied and prepare maps and reports that would help the prospector. No one will deny the

value of such work, and the Survey is carrying it on in several places; but the Survey, as a scientific organization, feels that up-to-date information on our leading districts is also of prime importance. The anatomy of mineralized districts serves the mining profession as a basis for the diagnosis of its mining problems, just as the anatomy of animals serves the medical fraternity as its basis for diagnosis, but whereas the entire animal body is available for study and may be dissected in a few hours, only the outermost parts of the earth's crust are available and deeper dissection in any one district is accomplished only over a period of years. Even the most thoroughly developed districts still leave much for interpretation, so the more facts that can be made available through repeated detailed studies the better. Even "post-mortem" reports are of value and well worth the few thousands of dollars they have cost, especially when it is realized that the most expensive of the Survey's reports, whether on dead, dormant, or vigorously active districts, has cost less than a single shaft or tunnel of moderate size, and contains information that may save many times its value by pointing out unfavorable as well as favorable conditions. Incidentally it may be questioned whether there are any Survey reports on mining districts that can be absolutely classified as "post-mortems." "Dead" districts are all subject to at least temporary revival. The preparation and publication of comprehensive reports on re-surveys of entire districts for the benefit of the public as well as local operators is obviously a Government enterprise, either state or Federal, depending on available personnel, facilities, and financial resources.

Cooperation with Public Organizations.—Especially during the last 10 years much of the work done by the Metals Section of the Survey has been in cooperation with Federal, state, and other public organizations, and the kinds of projects carried out include all those considered above, although comparatively little energy has been devoted to reconnaissance work. The general basis of cooperation with non-Federal organizations has been that the cost of field and office work by the geologist is shared equally by the cooperating parties and the services of laboratories, editors and illustrators are furnished by the Federal Survey. Publication has been financed in various ways, but the larger and more expensive reports are usually financed from Federal funds, while certain short reports and papers have been more promptly published as state bureau reports or in scientific journals. Some of the reports, on specific emergency problems that can be investigated in a short time, are prepared in the field and delivered promptly to the public organization interested. If published they are likely to appear only in mimeograph form. The men diverted to these emergency projects are, so far as possible, those most familiar with the areas involved.

The mutual advantage of cooperation is that the Federal Survey can make its work go twice as far and the other cooperating parties get two dollars' worth of work for the cost of one dollar. They also get the benefit of the Federal Survey's greater equipment and generally more experienced personnel, which includes specialists in all branches of geology who can be consulted or even called into the field when their help is needed. The cooperative projects are generally selected by the other cooperating party, but the work is done under Federal regulations and, as far as possible, by employees of the Federal Survey who are most suited for the work. Continuous cooperation insures an increasing knowledge of the region by those employed and a program that can be carried out over a period of years with cumulative results.

Relations with Geologists in Private Employ.—Where members of the Federal Survey and geologists in private employ have been engaged in the same district their relations have been most cordial, and with few exceptions mining companies have permitted or directed their geologists to supply the Survey geologist with appropriate available information. Although the Survey's geologists are forbidden by law to supply written information to private parties in advance of publication, they are encouraged to discuss the problems of single properties with the owners or their representatives, and these discussions are likely to be mutually beneficial.

Companies that maintain adequate geologic staffs obviously do not need the services of the Federal Survey in so far as the details of their own properties are concerned, but if their geologists are fully occupied in studying their own mines there is an obvious place for the Federal Survey in a study or re-study of the district as a whole or of the region that includes it. Although modern geologic work by company staffs is more detailed and much more time-consuming and expensive than that of Federal Survey geologists, whose visits are at best intermittent and whose energies must be spread over the entire district, it is as true as ever that the Federal men have the greater opportunity for correlations and comparative studies, and for providing a general setting for the intensive work that the companies want. Even if the company or private geologists have the time for such broader studies and are admitted to the mines of other companies, they are likely not to have the time to prepare a well organized report and their employers may not care to pay them for doing it. Because of these circumstances it appears that coordination of the work of company and Federal geologists can be developed further than it has been.

Topical Problems.—Topical studies by mining geologists of the Federal Survey have necessarily developed as byproducts of district or areal studies. After a good start on a topical study has developed, the geologist is encouraged to pursue it to a conclusion as steadily as his other assign-

ments permit. Some topics are simple and can be handled by one man, without detriment to his other work, but others are complex and time-consuming and may be too much for one individual to handle alone. Under such circumstances the Federal Survey geologist has the advantage of consultation and cooperation with his colleagues—including geologists, chemists and physicists, as well as library and laboratory facilities, both of the Survey and of other scientific bureaus in Washington. It would be ideal if a few well qualified men could be definitely assigned to topical studies that would fall within the province of such a scientific organization as the Federal Survey, but the very men most qualified must frequently be called upon, because of their qualifications and experience, to supply emergency and supervisory information in office or field, at the expense of progress in their own studies.

Occasionally topical investigations have been pursued by mining geologists outside the Survey who can divert themselves from their regular work for considerable intervals. The Federal Survey has always been glad to cooperate in these investigations in any feasible way—whether through consultation with its members, by parallel studies, or by making its facilities for work available. Worth-while results will be helpful to the mining industry and the engineering and geologic professions, no matter who produces them, and the Survey welcomes the opportunity to serve industry and science by helping others to produce results as well as by producing results entirely by itself.

General Source of Information.—The requests for information that reach it daily from Government bureaus, commercial organizations and individuals, either through the mails or by personal calls, require the Survey to serve as a living geologic encyclopedia, which is being continually brought up to date. Requested information pertaining to the mineral industries falls under all the subjects touched upon above, as well as the subjects of commodities, reserves and mineral economics. Questions that can be answered by the Bureaus of Mines, Foreign and Domestic Commerce, or Standards, or the General Land Office are referred to those bureaus, but questions within the Survey's province are constant reminders that the organization is generally looked to as a source of unbiased fundamental information, and must therefore keep itself informed, not only by bringing work already done up to date but by undertaking investigations of areas or problems that have thus far received little or no attention.

It seems likely, according to the present trend of affairs in general, that there will be more and more points of contact between the mining industries and governments regarding such subjects as tariff, taxation and control of output. Governmental action is obviously influenced by many cross currents, but is or should be ultimately based on available pertinent facts. The more accurate and comprehensive the fundamental

information, the better will be the chance that the action taken will be fair and helpful to the mining industry as a whole. This fundamental information obviously includes geologic data—the knowledge of natural conditions that control the occurrence, development and conservation of mineral resources. The United States Geological Survey is the logical supply point of this information, and the adequacy of supply is dependent on the kinds of work outlined above and the cordial cooperation of all interested in the mining industry.

[For discussion of this paper, see page 452.]

Function of State Surveys

By George H. Ashley,* Member A.I.M.E.

(New York Meeting, February, 1934)

Mining, including quarrying, dates back almost to the dawn of history, beginning almost with the beginning of what we call civilization. State surveys date back about 100 years. Evidently mining flourished for thousands of years before state surveys were thought of. Why should it not continue to flourish without state surveys?

First, it may be noted that as mining and civilization were contemporaneous, so state surveys and the science of geology were almost contemporaneous. As recently as 30 years ago the United States mineral laws were interpreted to mean that coal lands in the public domain were only those lands on which workable coal outcropped. The half billion acres of public land underlain by coal but on which it did not outcrop were treated as homestead lands and open to settlement.

Just what did the science of geology do to or for the mining industry? Until geology arose rocks or minerals or ores were where they were found. Their finding might be accidental, or might be the result of deliberate search or prospecting. In open, rocky country, with little or no vegetation, as in parts of the West, prospecting served very well, though at an enormous expenditure of human time and effort, if not money. The old saying that every dollar's worth of gold taken from the earth has cost two dollars may largely be charged to the time value of the usual method of prospecting.

Geology changed all that. The science is still young and it still labors under handicaps of immaturity and early errors. Geology, however, has gradually been discovering the relations and conditions under which the several mineral deposits occur. Its elaborate studies of exhausted or nearly exhausted mineral deposits has done for it what human autopsy has done for medicine and surgery. Perhaps in no field is this plainer than in the oil and gas industry. Note might also be made of several important coal fields in England and on the Continent, in which the coal is everywhere deeply buried.

Passing over the long period of growth during the past 100 years, geology today is prepared to offer the mining industry: first, a knowledge of the geologic conditions under which most minerals occur and to explore

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and map the areas within which these conditions exist; second, to elucidate the number, order, thickness, age and structure or lay of the many bedded rock formations, to serve as a guide, not only to where certain minerals or rock or mineral deposits may occur, but at what depth, if under the ground, how disposed or their structural lay, and by working out their changes from place to place, and if possible the causes of those changes, is in a position to forecast their possible value. With this information in hand any trained person should know how to go about a new mining venture with the chances of loss reduced to the minimum. If in addition to this he makes proper tests by drilling and analyses or assays, he has reduced mining from a gamble to a legitimate and, if proper mining and other methods are used, a profitable enterprise.

Where does a state geological survey enter this picture? I have suggested that with this information and proper mining and merchandising methods a mining project should be a profitable enterprise. If, however, to the other costs of mining and merchandising must be added the widespread studies to get the information that can be obtained by geology, still every dollar's worth of mineral recovered may cost two dollars. Were it possible for the entire mining industry of a region to form a closed corporation so as to spread the cost of this geologic work over the whole industry, it could doubtless be charged off against the sale price of the minerals. But geologic work is not of as much value to established mining enterprises as to new mining enterprises, some possibly not yet contemplated. Moreover, there are vast areas of land underlain by minerals of potential value, the actual value of which depends entirely on knowledge of the presence and worth of the mineral. Geologic work, by furnishing to owners of these lands this knowledge, may be of great value to them. Therefore they should share in its cost. But why stop there? This information will be of value to bankers asked to finance mining operations, to the purchaser of stocks and bonds of mining companies, to state or county officials charged with many duties toward the mineral industry and mineral reserves; in short, to all of us.

That is why from the very beginning of geology, the making of fundamental studies and broad field surveys have been looked on as a function of the state. A state geologic survey therefore looks upon itself as the geologic department of the mineral industry in the broader sense, including not only those actively engaged in mining but all those who through possession of mineral reserves, actual or possible, mining stock or other securities, or others who in any way form part of the industry or have dealings with it. Its function is to elucidate for the benefit of these people a general knowledge of the state's rocks, minerals, ores, waters and soils, as to their distribution, depth, and position in the earth, their quantity and quality, as well as the geography and topography of the state.

Question may arise as to just how far a state geologic survey should go in these matters. Undoubtedly the drift has been not only toward more accuracy but toward the gathering of an ever-increasing amount of local detail, to that extent relieving the mining industry of just so much preliminary testing or other geologic work. Doubtless the principle of the golden mean applies here as elsewhere. More to the point is the question: "How far will work by the survey result in a large saving in the conduct of the mining industry as a whole?" For example, here is a county with ten limestone beds of workable thickness. Their combined outcrops have a length of 1000 miles, and occur on 5000 farms or suburban estates. How far shall a state survey go in testing or determining the character of those limestones? Experience has shown that beds such as these are likely to vary less in character than in thickness and that a limited number of analyses, say between 100 and 500, would suffice to show the distinguishing characteristics of each of these limestones throughout the county, not only along the length of the outcrop but across its breadth, if the bed is thick. For the smaller figure, that means an analysis for each 10 miles of outcrop or for each 50 farms or other private lands. If then these 10 limestones are separately mapped, any landowner on whose land they occur is able to judge fairly of their values under his land. A mining company desiring a certain kind of limestone could at once see which, if any, of these limestones would serve their purpose and the map would show where it occurs.

If, however, the landowner or mining company contemplates the mining of one of those limestones it would be only wise to have a competent geologist make a detailed survey of the particular tract of land considered for development, to determine the thickness, character, and mining conditions of that land. Mining men as well as geologists know only too well how many geologic conditions may arise to ruin what would seem to be a perfectly safe bet. Indeed, the writer has described many instances in the coal fields where seemingly adequate core-drill testing failed to discover barren channels or extensive areas of thin coal.

As a matter of fact, few if any of the state surveys have up to the present undertaken as close mapping or testing as indicated above. That standard, however, has been set as something to be aimed at on the Pennsylvania Survey. In brief, it is my idea that a state survey should go so far as to make unnecessary extensive field surveys by those concerned with mineral development, but not so far as to make unnecessary local testing or valuation. On the one hand a geologic survey may indicate to inquiring landowners the possible or probable existence of mineral values on their land, what minerals are known or likely to be there, in what probable quantity, quality and depth; or, on the other, it may warn persons proposing certain developments that proper geologic conditions do not exist at the point of development. Most state surveys

have saved the citizens of their states, through such warnings, many times the total cost of the surveys.

There are, of course, many other ways in which a state geological survey may serve its going mineral industries, either directly, or by consultation by their employed geologist, such as interpreting the results of new or old drilling, identifying coal beds or oil and gas sands, offering solutions to puzzling situations encountered, suggesting byproduct recovery of other minerals, or passing along mining methods observed in one mine to others where it would be an improvement, and many others.

Another line of service is primarily to mineral-using industries, through answering inquiries as to raw materials, plant locations with reference to minerals desired, or water supplies. Or again to companies encountering problems involving geology or minerals of which there are a surprising number, ranging from new locations for lightning arresters that have proved ineffective (from telephone or power companies), to alignment of pipe lines through mining regions to avoid future danger of settling and disaster.

There might still be raised the question, "Why should we have state geological surveys when we have an efficient Federal Geological Survey?" Overlooking the fact that the state surveys antedated the national survey by a third of a century, I believe the following reasons are sufficient:

1. A state survey insures that the mineral industry of that state shall receive (more or less) adequate attention. A national survey is likely to be principally concerned with fundamental geology; that is, with those phases of geology that are country-wide or world-wide, or with problems affecting particularly the national domain; and where no state survey exists, the mineral industry of that state has to take its turn and may find little left. As a matter of fact, to a certain extent there has come to be a division of interests, the state surveys specializing on economic studies and the accumulating of economic data, while the national survey with its broader field has built up a strong personnel in the highly technical phases of the work and specialized in those phases.

2. In a state with large mineral industries, a state survey may be built up to meet the needs or desires of the mineral industry of that state independently of the support received by the national survey, as, for example, has been done in Illinois in recent years, where the state appropriation has run as high as $233,000 for a single year.

3. A system of state surveys spreads the cost of governmental geologic work, especially of the detailed geologic mapping and economic studies, and, assuming close coöperation between the national and state surveys, such as should exist, each supplements and extends the work of the other without overlapping in work or cost.

4. As in other matters, state surveys operating independently serve as experimental laboratories in so far as different methods of work or

publication are undertaken and, with proper cooperation between the several surveys, anything found to be of value by one is passed along to the others. It also tends to prevent a certain inbreeding of ideas and methods likely to occur if all work is controlled from one point.

5. A state survey, like a branch bank or store, permits ready consultation. This is especially helpful to owners of the smaller mineral industries or to the thousands of landowners interested in the minerals under their land. It is also an advantage in cutting the costs of survey work through reducing the travel to and from places to be studied and mapped, saving both time and money. The advantage in this respect increases with the distance from the national headquarters. Again, a state survey should be familiar with the work and findings of other surveys and may serve the citizens of its state with information about other states.

6. What is true in general is peculiarly true of the relation between the state geological survey and its state government. Just as the primary function of a national survey is to make maps and gather information that will be of direct service to the national government in matters of national defense, federal legislation, judicial decisions, the establishment of federal institutions, and in hundreds of other ways, so one of the functions of a state survey is to be ready at a moment's notice to supply information or opinions or even to make field examinations where necessary or desired by the state government. In a state like Pennsylvania, having large mineral interests, there is hardly a day that some question does not come from state governmental departments to the State Survey. Indeed, it has been estimated that the cost of turning to consulting geologists or the loss that would result if neither the survey nor other geologists were consulted, would go a long ways toward meeting the whole cost of a state survey.

A state government turns to its Geological Survey for a great variety of information, ranging from passing on proposed legislation to the identification for the State Police of mud found in a murder car; from passing on the safety of dam sites to supplying the Department of Justice with information in its court defense of state laws or in suits instituted against the state; from water supplies for new or old state institutions to cooperating in outlining courses of study being prepared by the Department of Public Instruction, and so on indefinitely. A state geological survey may be of inestimable value to the various departments of the state government.

[For discussion of this paper, see page 452.]

Service of the Surveys

By George W. Bain,* Associate Member A.I.M.E.

(New York Meeting, February, 1934)

The good work of the surveys supported by the different branches of the government needs little mention to geologists but is underappreciated by people at large. Geologists and engineers realize their usefulness and yet even from this group one hears occasionally an undercurrent of discontent about their work or the distribution of it. The very fact that discontent arises within and without this group and has drawn attention of legislative bodies of the country in the present time of stress means that a large number of people do not receive or do not realize that they receive benefit from these public works. This seems to be a clear indication that more than the relations between government surveys and the mining industry is involved and that if the mining industry is interested in continuation of the work of these surveys on the past scale they must consider the other survey divisions and their activity. Also, relations between government surveys and certain specialized types of mining have not been as close as they should be.

I have been employed in almost the entire range of fields offered to geologists and have studied closely the feeling of people towards geological service. Recently it has been a pleasure to be closely associated with men who were as deeply interested in civic welfare and affairs of state as in the financial success of a large industry developing natural resources. Previously I had seen service in a national survey, a state survey, summer employment by a large mining company exploring new property and detailed geological work for a large corporation. Major responsibility as a college instructor has left me free to view each of these assignments in unprejudiced fashion and at the same time study the relation of government surveys to large natural resource industries, average industrial and construction work and service to nongeologists and laymen.

Considerations Governing Geologic Public Service

Three groups of people must be satisfied by the surveys if dissatisfaction is to be dispelled. First there is a large group of people who pay taxes to support the government activities and must receive some service

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or be persuaded that they receive some, from almost every branch for which tax revenue is appropriated. Second, there is a legislative group which appropriates money raised by taxes and generally must be able to justify, or appear to justify, any expenditures which it ratifies. Thirdly there is a scientific and teaching group, which is small, composed of those who use the work of the surveys extensively and pay little towards its support but do a certain amount of publicizing of survey work to students who are generally unwilling to listen. This group should be the publicity department for the surveys, should indicate to the great body of students sent to college for purposes of obtaining a better understanding of living, how geology can make life more livable in part of that time devoted to pressing geological information into the minds of youth.

The Paying Group.—Support of surveys is appropriated from the general tax fund and in this it differs from road building, which is supposed to be paid, and the only expense paid, out of the gasoline tax. If national protection is excluded, the only service that natural resource industries receive in return for taxes paid is the service of the geological surveys and the Bureau of Mines; and what little service they receive should be good. Building and construction companies also pay taxes but derive only a small amount of benefit from the work of surveys and then only after considerable effort.

The balance of the survey cost, and it is a large balance, comes from companies and individuals that have no direct interest in natural resources, chiefly because they do not realize where many of their raw materials are obtained. Frequently, too, small investors will have a certain investment proposition submitted to them; they may not find it worth while to have a detailed investigation made but they may want to know what the geological survey thinks about conditions in such and such a district. Everybody travels and sees many interesting features, which he would like to understand; but the average survey bulletin, or for that matter even the best, is not within the grasp of even college-educated citizens. It takes a geologist to understand it; in other words, the bulletins are written by geologists for geologists and neither group pays a large part of the cost.

The Legislative Group.—Legislators are under pressure to cut costs of all work, especially work that they cannot justify. Much public work may appear unjustified to geologists and engineers, but opinion, or newspapers or other propaganda, have justified it to a sufficient number of people so that legislators do not have undue difficulty in indicating usefulness of expenditures to their constituency. Geological work has not been justified to the majority of the people who have made these men their representatives in government and geologists have not made an appreciable effort to indicate to the public that they are useful to the public. We might do well to take the attitude of Powell and give the

legislative body some interesting pictures of the country or educative descriptions of it.

The Scientific and Teaching Groups.—These make only a small contribution to the expense of maintenance of the surveys; in fact there is some doubt whether they pay even their share of national defense. They may be likened to the reporters of a newspaper; their work holds up the subscription list which pays a negligible part of the cost of operation; if their work weakens or becomes less attractive the subscription list drops and advertising return decreases, to the loss of the publication. The staffs of the surveys have as a major duty, if they wish to survive, the task of preparing enough reports of general interest to hold a subscription list.

Summary of Suggestions

Most illustrative examples are taken from work in Vermont but a wider range is included to show the general applicability of the major thesis, that applicability of service is the measure of its usefulness. No individual member of a survey need meet all or any of the inadequacies of the present service but a survey or surveys as a group must meet at least a majority of them to stem the undercurrent of discontent. The following is largely a series of suggestions classified from the viewpoint of the three large groups concerned with the geological surveys.

The Operators' Needs

1. Among geologists, especially members of the national and state surveys, exists a decided hesitancy to learn and use the operators' terms for features in the region where both are interested. This causes operators to withhold information, introduces misunderstanding and causes geological reports to be looked upon with suspicion.

2. Dodging the question or giving an explanation that may not be the explanation is a favorite practice of geologists. If information is not sufficient to justify the explanation offered, a statement to that effect is usually appreciated.

3. View the expense account from the other man's viewpoint. There is often a tendency in pure-science geologists to run off upon interesting side problems and this usually holds up the expense account and time.

4. Many of the problems worked upon for the operators of a mine or quarry industry are of local application and have been solved by their engineers, from whom the information could be obtained by gaining their confidence. Problems of a distinct geological type upon which operators desire information are often omitted or treated briefly; these usually are detailed information about regional aspects of the deposits which require a more general picture than is to be had from the operated section.

5. Usually descriptions of prospects contain no statement of structures governing localization. Statement of these geological features is essential to enable the small investor to obtain an opinion on its value without sending a competent consulting geologist to examine the place. Inclusion of this information would enable him to obtain a tentative opinion from a geologist who had not studied the place in detail. While this might curtail the work of consulting geologists for a time, the confidence established in geological work among an increased group of people would divert to this profession much of the funds now absorbed in speculation.

The Legislators' Needs

1. The legislator should be furnished with arguments of the usefulness of the surveys, which could be sent to at least a large part of his constituency.
2. Geologic information must be supplied to voters for this representative, in such form that they not only can read it but will read it.
3. The scientific side for the few is usually so overemphasized that the educational side for the majority is submerged.

The Scientific and Teaching Groups

1. General popular style and informational publications are underemphasized and deficient in number.
2. Hesitancy of geologists to contribute papers to the press, written in popular style but with scientific accuracy, is responsible for the poor opinion of the science among laymen.
3. Many instructors teach geology without first explaining the general usefulness thereof. After all, only about one student in two hundred ever uses the subject in the form in which it was presented to him by his teacher.
4. There is a strong leaning among geologists to be pathologists and not to attempt to use their diagnosis of a case in an effort to apply a cure; that is, they do not become physicians.

Service of the Surveys

Geologists employed on national surveys are men of long experience in geological work or men who have specialized in the study of geology in universities. Specifically, they are geology-conscious and unconscious to most other things; frequently the minor details of the temperature and pressure of formation of a mineral deposit take precedence over the features that indicate the trend of the oreshoots and extent of the deposit as a whole.(1)* While conditions of formation are interesting and

* References are at the end of the paper.

informative, they in themselves were used by the author of that method of study as a means to an end and that to facilitate the understanding of variations in mineral deposits.[2] Too often geologists have made the means the end; they should take stock of the limitations caused by specialization and attempt to fill out the deficiency by study of the limitations in understanding by the layman and company management.

Service Rendered Operating Companies

Operating companies usually are interested to know something about the deposit they are working outside the section they visit daily in inspecting work. Usually the information published upon the worked part of a deposit is information imparted by operators, not to them. Simple descriptive information is of little value unless it is arranged in such fashion that the reader cannot avoid drawing a mental conclusion from the facts as presented. Lastly, certain features may receive an explanation and sometimes that explanation may not be the only one or even the correct one. Instances have arisen where a geologist, because he felt that he must have an explanation for everything geological, has presented an explanation as fact and the explanation selected has been the wrong one; often this practice has destroyed completely faith in geology; it would have been better if that geologist had admitted the possibility of some other explanation, or even had a millstone hanged about his neck and been cast into the sea. I propose to illustrate many of these features with specific examples and beseech those who may have cause to be offended to overlook the offense and consider the fact that the author too has sinned in this respect in acquiring experience.

Helpful Work.—The early work at Leadville, Colorado, indicated that the oreshoots were in the blue Leadville limestone and were limited principally to that part of the limestone below the intrusive sheets of white or alaskite porphyry.[3] This observation indicated which parts of the region merited exploration and made possible a great saving in cost of development of this camp. This simple structural observation had no argument of paragenesis, temperature and pressure or other complications. It was simple observation of a regional characteristic which each operator could not make by use of his own mine only; the latter details he could obtain for himself.

Rare instances appear from time to time in which a geologist has been of direct help. The late Willet G. Miller gave the blacksmith La Rose the full benefit of his discovery of silver in the erythrite and niccolite from the cut of the Temiskaming and Northern Ontario Railway at what later became Cobalt.[4] This is just one instance of the integrity of Dr. Miller and its help in establishing the importance of geology in the mind of people of Ontario. In more recent years Cairnes, of the Geologi-

cal Survey of Canada, has been of almost equal service in giving to the country a large magnesite deposit in British Columbia.[5]

Correct but Not Always Applicable Information.—More often the geologist is a mere assistant in the general development of a region; he can tell prospectors which regions give most promise and give them an opinion on an exploration plan of their claims in much the same manner that geologists of large corporations give similar assistance when work reaches a more advanced stage. The advice on areas suitable for prospecting, while correct information, often is not applicable and at other times is decidedly misleading. Prospecting around the edge of granite batholiths in northern Quebec and Ontario was encouraged formerly by the surveys on the basis that the deposits were believed to have originated in these intrusives. James indicates clearly that mineral deposits are not to be expected near the contacts of these major granite batholiths.[6] Whether the deposits originated in these batholiths or not is unimportant and the Howey mine is the only one to appear within three miles of the border of a major intrusive. Some feature was more important than the granites in determining which regions were suitable ones for mineralization.

Sometimes this error of presenting the incorrect hypothesis is more damaging than in the case described. The Pearl Lake gold lodes in northern Ontario occur in association with a quartz-porphyry intrusive and the solutions that deposited the ore have been ascribed repeatedly to this intrusive. While this view is not accepted at present,[1,8] it retarded development of one property in the past. Distribution of the veins made it very evident that they occurred on the footwall side of the intrusive only and raked under it to the east (Fig. 1). If this structural distribution had been emphasized, instead of the theoretical origin, at least one of the mines would have been developed much more rapidly and investors would have been more certain of one place in which to put their funds.

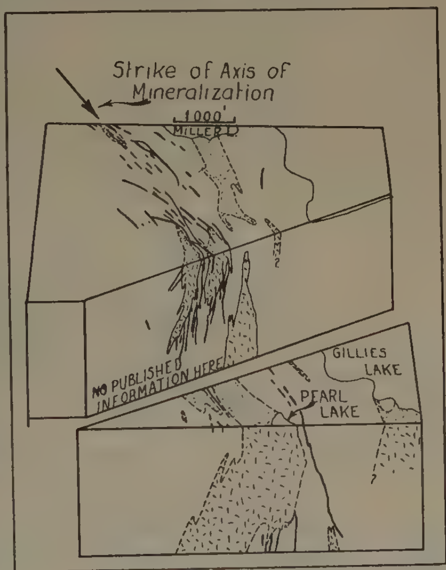

FIG. 1.—BLOCK DIAGRAM OF EAST END OF PEARL LAKE AREA.

Diagram shows veins (black) raking under porphyry (stippled). Absence of surface veins in porphyry is no indication that they do not occur below it. This block prepared to scale from sections published by Ontario Bureau of Mines.

The Tendency to Offer an Explanation.—A case of a geologist attempting to explain everything geological occurred at West Rutland, Vermont;

in fact, West Rutland seems to be the prize place for geological explanations. A line of quarries extends almost north and south along a marble deposit, to where swamp and meadowland cover it; another quarry occurs about ¾ mile south and 1000 ft. to west of the line; marble in it is identical and in identical sequence with that farther to the east. This occurrence was pointed out to a visiting geologist who had received numerous favors from the quarry company, and he explained the offset as due to a

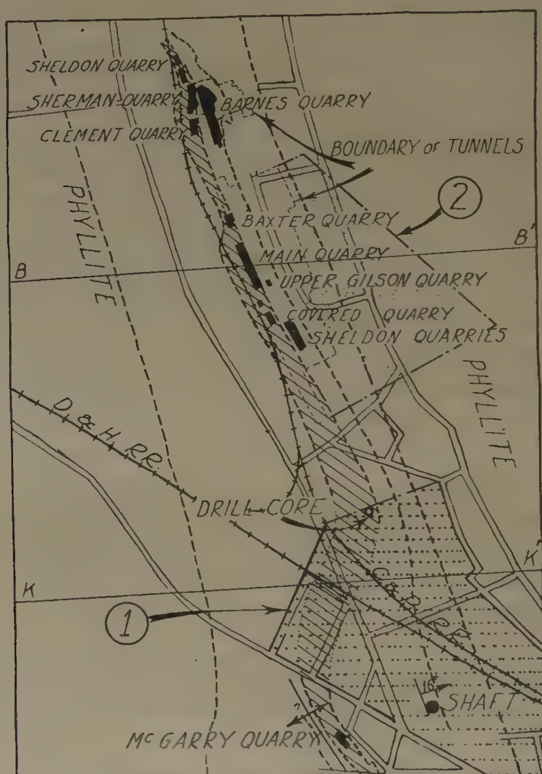

FIG. 2.—MAP OF WEST RUTLAND MARBLE DEPOSIT.

Main marble deposit cross-hatched. Supposed fault followed line of D. & H. R.R. Property affected by assumption of a fault offset is in dotted lines (1). Property affected by assumption of a synclinal structure for the valley is stippled (2). See also Fig. 3.

fault. This meant that land along the line of the old quarries was worthless as a marble prospect and land titles and tax arrears by individual owners were allowed to get into quite a snarl. The specific details along the northern line of quarries show that at intervals the beds flatten out as they pitch south and that these flattenings offset the outcrop of a bed to the west (Fig. 2). That one of these flattenings of major proportions offset the deposit beneath the soil cover seems to be fairly definitely established by a shaft sunk through the soil cover. Needless to say, that

bit of bad information has not increased the standing of geologists in that district.

The most recent map of this same section indicates a synclinal structure for the West Rutland valley.[9] Had the geologist who made this map and the accompanying structure section gone down into the quarries to see how far under the hill their operations went he would have realized the error on the section. (See Fig. 3.) Had this section appeared at an earlier date it would have resulted in a title snarl similar to that mentioned above. In this case the trouble with the explanation was lack of cooperation.

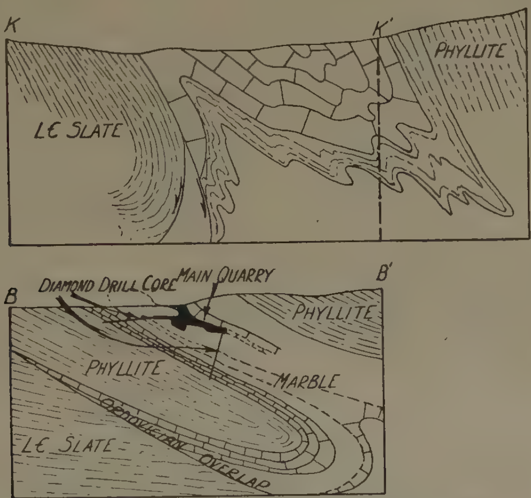

Fig. 3.—Section across West Rutland marble deposit, BB' according to Bain and KK' according to Keith.

No rock exposed along line of section given by Keith so that definite criticism except by comparison is difficult. On section BB', main quarry has followed marble bed down far enough to indicate a fairly continuous dip to the right. Diamond drillings here and at Albertson quarry farther north indicate impossibility of phyllite underlying marble.

Help Where It Is Not Needed.—Fault structures always seem to catch the geologist's attention and he has an irresistible desire to run them down. Often this is not necessary to mining operations. A number of pre-ore faults cut off the veins in the McIntyre mine almost as effectively as if they were post-ore (Fig. 4). Solution of such a fault would be futile because afterwards there would be no vein on the offset section. The important piece of work is to determine the relative age of ore and fault and study only those that are post-ore.

Geologists working in quarry districts usually spend much time mapping the joint directions in order to tell the quarrymen how to run their quarry. This is more or less unnecessary; quarrymen know how to avoid joints and save a maximum of stone, otherwise as a company they would

soon cease operations. One feature in which quarrymen are interested is groupings of joints, especially the thickness and position of a closely spaced group which no amount of care in laying out the quarry can avoid. Geologists can be of great help in indicating the position of such "nests," the depth at which they may be encountered, and the thickness they will have at that place (Fig. 5).

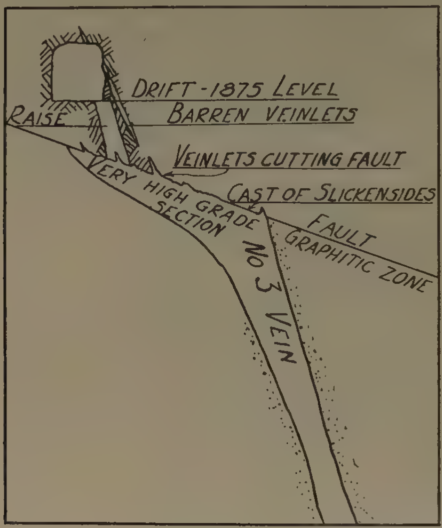

FIG. 4.—SKETCH OF RELATIONS ALONG PRE-ORE FAULT IN PEARL LAKE DISTRICT.
Casts of slickensides in quartz indicate presence of fault along the graphitic zone. Small quartz stringers cut through part of slickensides, indicating that mineralization is later. Although rocks are offset, the vein is not; veinlets are barren above and very high grade immediately below this fault. Solution of fault movement is unimportant to development of deposit.

The average company is willing to cooperate with almost any recognized group that may be studying a deposit for the general good. This, of course, is assuming that they have not been imposed upon or misrepresented or betrayed by a previous visitor, and while this happens occasionally, fortunately it is not frequent. I know of one such case directly and another of earlier date by hearsay; no geologist should take offense if his visit is looked upon with some suspicion, for not all may be as sincere as he intends to be. In return for cooperation and assistance rendered, the average company expects to receive some return in service or information which its staff of engineers is not equipped to obtain. The geologist is in a "tough spot" when this happens to be confidential information from a neighboring property, but usually a company is satisfied to receive help other than this type; in any event, the only choice is to refuse to divulge confidential information because, failing to do so, you lose the confidence of those whose confidence you wish to obtain.

Service Rendered Consuming Companies

This field of service is not of such outstanding use to mining products as to building materials but in all fields it has its use. The very recalcitrant Sullivan ore from Kimberly, B. C., has a good feature which was overlooked for a long time and never was recognized by geologists until metallurgists called it to their attention; the manganese minerals present are just sufficient to help out electrolytic treatment. In other cases

identification of the gold and silver associates by metallographers has helped the oil flotation men to a considerable extent.[10]

The gold in the Howey ore occurs with galena, sphalerite and coarse pyrite, or along fractures weakened by sericite flakes parallel to their walls. Coarse crushing breaks the rock on these weaknesses and exposes the gold to cyanide solution or any other treatment that might be used to recover it. From the time of earliest examination of these ores it was evident that the gold could be extracted at only a fraction of the Pearl Lake or Kirkland Lake costs.

Architects and construction companies have received least assistance, deserve most and need it most. Only geologists associated with this group

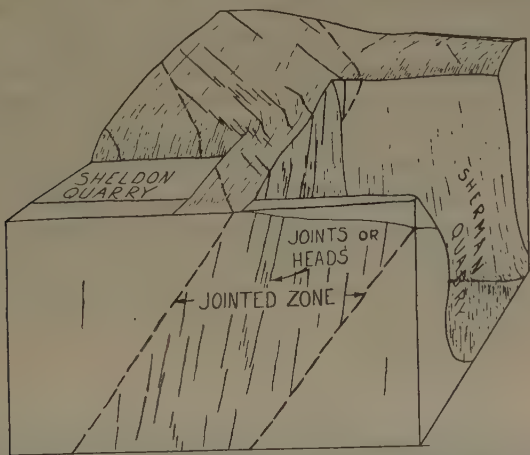

FIG. 5.—SKETCH OF NORTH END OF SHERMAN QUARRY TO SHOW "NEST" OF JOINTS AND DISTINCTION OF PROBLEM OF JOINTING FROM THAT OF GROUPS OF JOINTS.

Quarry problem is to determine depth where joint system will pass out of quarry property. Position of joints does not conform to position of joint zone in either strike or dip. Position of joint zone and not the joints is problem confronting quarrymen.

can realize how little information it has at its disposal when selecting a building stone. An outstanding case of help to this group was Loughlin's identification of laumontite as the cause of disintegration of the anorthosite used in a Los Angeles building.[11] This contribution can be considered no more than a start because there exists no valid reason why architects should not have available information upon the properties of all stones that are to be used in construction, and an improper selection can be no fault but their own.

If we go over the literature on granite, marble, limestone, slate or sandstone we will find almost no statement of their relative durability under any set of conditions, let alone all sorts of conditions. Yet this is information that a survey, supported by taxes accepted partly from architects and contractors and realtors, is expected to give. Certainly the Vermont State Survey, with building materials a major state product,

has been extremely backward in furnishing this information on its products. Most of the statements on this subject have been quoted from author to author and usually the first one was wrong because of nonrepresentative material or poor methods of study. I know because I have just entered the middle stage of an investigation into this sort of thing for a large company, which wishes to have monuments to its good products—not its bad ones. It wishes to be able to furnish to architects reliable information on durability of material it supplies.

Occasionally, through ignorance or carelessness or thoughtlessness, the wrong stone will receive publicity and because of this be held up as the type for a region. The only buildings of Vermont marble figured by Dale[(12)] are made of Dorset marble. These are the most unsuitable exterior marbles of any quarried in Vermont, and the New York Public library is a good example; not one Dorset quarry is active today; builders have found out for themselves that this marble is not durable enough in our climate, and the rock exposures should have told geologists the same story years ago. Contrast with the New York Public library, the Red Cross building in Washington or the Arlington Memorial. The field evidence of durability is against the Dorset marbles, just as it is in favor of the Danby and Pittsford Valley ones, and it seems incumbent upon geologists to indicate to the best of their ability the suitability or unsuitability of these stones.

Service to the General Public

The surveys are supported by a buying public, which, however much it may like to be fooled, really wishes to receive something from the body of public servants it supports. The public can receive something directly from the geological surveys in two ways; namely, (1) from investment information or information that may be used indirectly in making investments, and (2) by receiving readable descriptive literature featuring certain parts of the country that may be visited on Sunday drives or on vacations.

Information for the Investor.—Canada has enjoyed, since 1923, a great mining boom and everybody has become "mine conscious." This is not so true in this country, where we seem to have become utilities unconscious. The basin of the Harricana and Bell rivers is one of the exploited regions and the literature on it gives few indications of the localization of the deposits, so that the reader may form some opinion of their future continuations. The writer's own paper[(13)] is almost as deficient as the others[(14)] in this respect. In this day of soaring gold prices almost any prospect in that region could be recommended but as a stable investment probably not more than three of the properties under development in 1925 had sufficient system to the occurrence of the veins to be consid-

ered potential long-time producers. It has been pointed out that no deposit in northern Canada that lacks regularity or system to the occurrence of its veins has ever paid back on its investment;[15] if some system of distribution of the veins cannot be recognized, search for new ones in the vicinity is so haphazard that the prospect cannot be recommended. It would seem to be incumbent upon men of a government survey to point out the presence or absence of system to the veins upon any group of claims. At the same time a certain amount of caution should be exercised to avoid diversion of money from good prospects. The early difficulties of the Lake Shore mine at Kirkland Lake, Ontario, represent one such instance; yet here the trouble was largely poor geology. A fault of the magnitude of that on the developed Teck Hughes property could hardly be expected to die out in a distance of less than a mile, and reasonable chance existed that some sort of mineralization existed for the length of the breccia zone.

Every dollar that goes into a poor investment in a natural resource industry, whether it be a northern Ontario mine or a Dorset marble quarry, is a dollar diverted from a meritorious prospect. The lower the number of dissatisfied investors in the industry or its products, the greater will be the number supporting the natural resource industries and the greater will be the revenue available for surveys and investigations in this field.

Educational Information.—Popular literature and publicizing of interesting geological features reaches a greater number of people than any other form of geological work. Dr. John M. Clarke, late director of the New York State Museum, was one of the most able men ever assigned the task of obtaining funds from a legislature. He did this in two ways and both are a monument to his life work. The parks he established throughout the state bring to the people at large and preserve for them in attractive fashion many simple and outstanding geological features. The little group of fossil trees near the Ashokan reservoir intrigue the passer-by and the explanation of the Cryptozoon reefs at Lester Park, N. Y., attract many visitors yearly. Publications issued during Clarke's administration were varied; along with very technical ones on geology and botany appeared occasional ones on wild flowers, fruits, fossils, and minerals written in popular language which are the delight of many a layman.

The fresh sally along a similar line by the Virginia Geological Survey is commendable.[16] "Caverns of Virginia" is a book that appeals to every layman and doubtless will repay its cost to Virginia many times in added tourist trade and an inestimable amount in interest to the average person. The traveller along the Jackson-Lee highway cannot help but stop to see some of these natural features, provided these popular books are kept in sight in hostels along the way.

A similar project would be advantageous to Vermont. The variety of scenery in the state attracts many people annually. The Long Trail on the summits of the Green Mountains is a delightful path to follow and is broken into short sections by cross-highways. Yet in all the years that the Vermont State Survey has been in operation it has published no bulletin written in simple language to indicate to the visitor the interesting historical background of the scenic features along its many picturesque roads or the Long Trail. I know such features interest these people because while working through the state I have had many interesting times explaining to Vermonters the features of the country around them. This sort of work can be made more understandable if photographic illustrations have structure sections across the front or base to show influence of subsurface rock upon topography. Development diagrams also help. In this way the hills will come to be a story and not simply another piece of scenery.

The Legislative Group

The expenditures of all surveys are appropriated by the legislative group elected by and representing the general public. This group is called upon to expend the money entrusted to it in such manner that its action can be justified to the people it represents and it will find this extremely difficult if the action is not justified in its own mind or sentiment is not stirred up in favor of the expenditures. Sometimes a small expenditure is made and is not questioned because of the smallness thereof. This is true of the two thousand dollars appropriated biennially for the Vermont State survey, which has commended itself neither to the general public nor to the large industries and so has nobody to advertise it to the legislature. The same argument can apply in lesser degree to the major geological surveys of this continent.

The Ontario Bureau of Mines is an exception to this rule: whatever the mistakes it may have made, it has commended itself to a sufficient number of hopeful prospectors and miners to receive strong support from the government. The work of the coal and water-supply divisions of the United States Geological Survey have supplied information to enough people to attract the attention of a part of the legislative body. The water-supply division furnishes engineers with accurate information on the run-off of respective regions, so that available power at any place at any time of the year can be estimated closely and easily. The records are important in flood-control work and the importance of flood control needs no press agency in a large part of the Mississippi and Colorado river basins. Ranches in artesian basins in New Mexico and Arizona have benefited likewise by the research of this division in subjects of well leaks and depth of aquifers.

Vermont is a great producer of building stone. The state survey could render a great service to the state income from this source by keeping the building trades authoritatively informed of the properties of the stone produced. The men employed in the industry would benefit in more continuous employment and be more satisfied with actions of those representing them in government, and builders would be better informed on the materials they were using.

The merits of talc from this state, New York and Virginia have never been compared for the many purposes to which they are put. They differ, and I am certain that industry would benefit if the properties of all talcs were known. Use of the wrong talc in one instance frequently "black-balls" all talc for that use; accurate knowledge of the differences might hit one deposit for a time but in the end the entire talc industry would benefit.

These same criticisms apply not only to Vermont but to Massachusetts, New Hampshire and Maine, where surveys have not been continued because of nonbeneficial service, and to many other states where the service could be improved without much effort. It is in times of stress that dissatisfaction rears its head but the dissatisfaction is born and bred in advance by inaction and becomes irritated only by additional troubles. Keep not only the legislators satisfied that you are doing something, but also make the people who may elect a new legislature realize that they are receiving service. A common plank in an election platform is reduction of cost of government; usually the branch easiest to threaten with a cut, or even cut, is that least known to the public or that in which the public thinks it is least interested. And of these I think the Geological Surveys head the list.

Service to the Scientific and Teaching Group

Teachers are simply a part of the survey service. They are dependent upon the surveys for much of their information and the duty devolves upon them to impress their students with the importance of the work being done to maintain interest in and support for this source of information. Sometimes the surveys are lax in supplying information to the teaching group but more often the teachers are backward in acknowledging the source of their information. But sometimes the information supplied is such that the teacher is forced to condemn the source.

Lack or Poor Quality of Information.—The state of Vermont has very little published information on its geology, so that teachers have little to recommend or condemn. Most of the information is simple description with little plan or relation between the different units; in addition, much of the work in the eastern part of the state is incorrect. Maps show areas of ultrabasics one to two miles long;[17] I have checked most of these and find that many indicated to be of this size are not over 300 ft. long.

Similarly, large areas mapped as limestone are graywacke and gneiss, and some are carbonated intrusives. Naturally, teachers cannot support the work of this survey as it was conducted in past years. While this criticism applies to very few surveys, it can be used in debate by anyone opposed to continuing their work.

Acknowledgments to the Surveys.—Chamberlin and Salisbury refer to the source of information repeatedly in their textbooks,[18] and the same practice is adopted by Tarr and Martin[19] and by Ries.[20] Books of more recent vintage give nobody credit for their information, unless it is in a small place in the preface which no student reads. In all probability the present author has been the worst offender of the lot on this charge. Textbooks are read more widely than any other form of geologic literature at the present time and it is in them that the importance of surveys as sources ought to be brought to the attention of students and other readers if the surveys are to receive the support they need.

Self-help by the Surveys.—The late Dr. John M. Clarke took all of these obstacles at one leap by going directly to the general public and attempting to educate them in some few general features by small parks which he established. Similar attempts to popularize geology have been made by bulletin boards along some roads through Oklahoma. This is good work but not always possible or attractive. It seems as though, at about one-year intervals, a survey ought to be able to issue a general, moderately popular bulletin for anyone to read and all to enjoy and understand. "Geology of Canada"[21] was a very popular memoir issued by the Geological Survey of Canada. It is almost too technical for the average reader and might be illustrated better, but its wide use testifies to the broad public interest in this subject in Canada. The same interest should exist anywhere else provided the subject is presented so that the average reader can follow the text. The guidebooks along the main rail routes through the western states are an excellent attempt to reach a wider group of people. However, the structure sections would be more realistic to the average person if they had a landscape as a background, so that surface expression could indicate the essentials of the subsurface structure on the sections.

Conclusion

It is almost impossible to maintain a public service for one group of interests. If the hundred-odd million people in the United States concluded that the Navy was for the Navy and not for their protection, the Navy would be short-lived. If the Department of Agriculture helped only the farmers and did not keep check on food until it was delivered to the consumer, it would encounter difficulties greater than the Geological Survey ever has had. The same can be said of the Army, the Department of Commerce or any other branch of the government service. The geological surveys are of value to the mining industry,

whatever the mistakes individual members may make; it can become of greater value but the mining industry should not claim even a major part of the time of the service if it wishes the service to continue. The present close association of geology with metalliferous mining has weaned the geological surveys away from so many people to such a degree that they have lost interest in it. This interest must be recaptured.

Bibliography

1. A. G. Burrows: The Porcupine Gold Area. Ont. Dept. Mines (1924) **33**, pt. 2 45–46.
2. W. Lindgren: Mineral Deposits. Ed. 1, 178. New York, 1913. McGraw Hill Book Co.
3. S. F. Emmons: Geology and Mining Industry of Leadville. U.S. Geol. Survey *Mon.* 12 (1886) 375.
4. W. G. Miller: Cobalt-nickel Arsenides and Silver. Ont. Bur. Mines (1913) **19**, pt. 2, 3. (Literature is very indefinite on the discoverer of Cobalt. Specimens reached Arthur Ferland of Haileybury, who submitted them to T. W. Gibson and he referred the minerals to W. G. Miller. Up to this time no silver had been recognized and Miller was the first to realize the value of the find.)
5. C. E. Cairnes: Some Mineral Occurrences in the Vicinity of Cranbrook, B. C. Geol. Survey Canada Summary Rept. of 1932 (1933) pt. A2, 101–194.
6. W. F. James: The Rouyn Map Area. *Can. Min. Jnl.* (May 2, 1924).
7. Reference 1, 44.
8. L. C. Graton, McKinstry and others: Outstanding Features of Hollinger Geology. *Bull.* Can. Inst. Min. and Met. (1933) 17–19.
9. A. Keith: Outline of the Structure and Stratigraphy of Northwestern Vermont. XVI Int. Geol. Cong., Guidebook 1 (1933) plate 8.
10. A. W. Hahn: Silver-bearing Minerals of Some Ores from the Tintic Mining District. *Trans.* A.I.M.E. (1929) **85.**
11. G. F. Loughlin: An Interesting Case of Dangerous Aggregate. *Proc.* Amer. Concrete Inst. (1923) **19,** 150–153.
12. T. N. Dale: Commercial Marbles of Western Vermont. U. S. Geol. Survey *Bull.* 521 (1912) plate 11.
13. G. W. Bain: Geology and Mineral Deposits of the Harricanaw and Bell River Basins. *Bull.* Can. Inst. Min. and Met. (1927) 201–247.
14. H. C. Cooke, W. F. James and J. B. Mawdsley: Geology of the Rouyn-Harricanaw Region, Quebec. Can. Geol. Survey *Mem.* 166 (1932) 158, 171–173, 234–301.
15. G. W. Bain: Structure of Gold-bearing Quartz in Northern Ontario and Quebec. A.I.M.E. *Tech. Pub.* 327 (1930) 43.
16. W. M. McGill: Caverns of Virginia. Va. Geol. Survey *Bull.* 35 (1933). 187 pages.
17. C. H. Richardson: Geology and Petrography of Reading, Cavendish, Baltimore and Chester, Vermont. *Rept.* Vt. State Geol. (1928) **16,** 210–211.
18. T. C. Chamberlain and R. D. Salisbury: Geology. New York. Henry Holt & Co.
19. R. S. Tarr and L. Martin: College Physiography. New York, 1921. The Macmillan Co.
20. H. Ries and T. L. Watson: Engineering Geology. New York, 1915. John Wiley & Sons.
21. G. A. Young: Geology and Economic Minerals of Canada. Can. Geol. Survey, Econ. Geol. [1] (1926).

[For discussion of this paper, see page 452.]

Value of the Geological Surveys

By Hugh M. Roberts,* Member A.I.M.E.

(New York Meeting, February, 1934)

The important place in the economic life of the country that is occupied by the United States Geological Survey and the various state surveys is appreciated by most members of our Institute. To the public at large, the functions of these surveys are no doubt largely unknown, and taken for granted. Possibly a realization of the value of the work of these government branches is brought home most fully to that group of our members whose duties as examining engineers and mining geologists take them to mines and prospects in many different parts. The examining engineer or geologist is usually seeking for a judgment on the value of an enterprise from the standpoint of the useful minerals that may or may not be present; he must also attempt some prediction as to future market prices. On his opinion rests the determination of the expenditure of money, which rendered into other language means the expenditure of human effort.

An opinion on an exploring venture or the reasoning out of the probable extensions of an orebody requires among many other things a background of knowledge covering the geologic horizons not only of an immediate area but of the surrounding area, a knowledge of the structural geology and of the causes that have operated to form the ores as they are. The great storehouses of this knowledge are the statistics, reports and maps issued by the various geological surveys. They supply the groundwork for additional observations. To these, reference is always made when going into a new district. The technique of work in the field and laboratory, and to some extent the hypotheses that underlie our methods of approach, have been formed by men such as Van Hise, Leith, Kemp, Spurr, Emmons and Lindgren, who developed their powers in the service of the geological surveys. In addition to whatever originality of thought, or power to observe facts and analyze them, may be our portion, we require, in the application of the arts and sciences, a knowledge of what has already been done. We stand on the shoulders of those who have gone before, and the extent of our vision often depends upon the thoroughness with which we form earlier work into one whole and make use of it.

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Geologic Map of the United States

A noticeable example of this integrating function of the U. S. Geological Survey is the recently published Geologic Map of the United States, issued in 1932. The labors of four generations of geologists have been summarized on this map. As an illustration, consider for a moment the portion of it most familiar to those who live in the Lake Superior region. Glancing just below the outward surface of the map, with its wholly modern aspect, we may see, not too deeply buried, the work of the fearless Douglass Houghton, who a century ago began the study of the copper-bearing rocks of Keweenaw Point, and while yet a young man lost his life in a storm on Lake Superior. As State Geologist he was the prophet and forerunner of the copper-mining industry: Quincey and Agassiz followed, developing mines where he had laid out the trail. Looking closely we may catch sight of the footprints of Foster and Whitney, "United States geologists," mingled as their footprints were with the "traces of otter and beaver and the tracks of the bear, the wolf or the deer impressed upon the sands by the margin of the river where they drew up their canoes and camped beneath the shelter of a group of pines." Their researches on the iron-ore districts of Michigan were made known in 1851, and have since been incorporated into later work. But turning over the pages of their report, with its fine old woodcuts and lithographs, we get a true feeling of the wilderness on Lake Superior, its latent power and potentiality, still hidden before the future, as Foster and Whitney, with others, first began to understand the operation of geologic forces and engaged in a study of the mineral deposits. These mineral deposits have been the economic mainstay of the region, the chief factors that have permitted the growth of strength in the people who came to occupy it. Nor can we doubt that this report in its day was largely responsible for the interest of many a Pennsylvania or Ohio iron merchant, who, reading it at his fireside, was led to venture in iron mines on Lake Superior, and may it be said, to his profit.

Practical Results of Scientific Effort in Lake Superior District

The Lake Superior district has been singularly indebted to its scientific men for practical results. Quoting from *Monograph* 52, U.S.G.S.:

> Iron was first discovered in 1844, near the site of Negaunee by the Government linear surveying party in charge of William A. Burt, himself under the direction of Douglass Houghton. The Michigan legislature having failed in 1843 to renew appropriations for the Michigan Survey, Dr. Houghton had turned to the Federal Government and had succeeded in procuring an additional allowance per mile for geologic work in connection with the linear survey of the Upper Peninsula which had already been begun, and he himself took the contract for the linear survey in order to have direction of the work.

Burt was the inventor of the solar compass, and utilizing the instrument on this particular line of survey near Negaunee, it was the extreme varia-

tion of the magnetic needle that caused him to send his survey crew searching for the cause. It is related that his chief pride was not in having discovered iron ore but in having been the inventor of an instrument that permitted the rapid determination of the true meridian, regardless of the aberration of the magnetic needle. Whoever has occasion to retrace any of the linear surveys made by William A. Burt, and to compare it with many other surveys made during the same period, comes away with a feeling of respect for the quality of the man, who in a remote region, answerable only to himself, did so faithful a piece of work. Burt lived and died a poor man, but his name will be long remembered, when those who became wealthy by platting pine lands as swamps are as anonymous as the pike that swam in the waters of the lakes. In the same historic background with Houghton and Burt are Major T. B. Brooks, Robert Dale Owen, Alexander Winchell, Raphael Pumpelly—all true men of science. Later and more plainly marked is the work of Roland D. Irving and Charles R. Van Hise, who, in studying the Gogebic Range of Michigan, first formulated the principles underlying the concentration of Lake Superior iron ores, which have been the guide of the explorer and miner since.

Present Stage of Geologic Map and Modern Geologic Reports

Glancing again at the portion of the Geologic Map of the United States that represents the Lake Superior district, we see that it reveals most prominently the present stage of the advancement of science. The boundaries and correlations shown are more largely the work of this and the immediately preceding generation of geologists. We are reminded of one of the finest works of the U. S. Geological Survey, *Monograph* 52, by Van Hise and Leith, on the Geology of the Lake Superior Region, which consolidates that which went before, contains the researches by Mead on the characteristics of the iron ores and lays out a pattern for all work in pre-Cambrian geology. Also incorporated in the portion of the Geologic Map of the United States that we have been considering is the work of Emmons, Grout, Hotchkiss, Broderick, Schwartz, Gruner, and many others who have advanced the work of the national or state surveys since the year 1911, when *Monograph* 52 was published.

In all of the mining districts in the region, detailed topographic and geological maps are available; monographs and reports that enable an understanding of the geology and the geologic processes that have operated. These are questions that concern vitally all phases of exploration for new ore deposits and the utilization of those now known. A study of these problems has hitherto kept pace with the advance of science and the developments of the time. As recently as 1929, the Wisconsin Geological Survey has published a monograph on the Geology

of the Gogebic Iron Range in Wisconsin, by H. R. Aldrich. This describes the Keweenawan thrust faulting, the intrusion of the gabbro laccolith into Huronian and Keweenawan rocks, and the consequent effects upon the structure of the Huronian series with the contained iron-bearing formations. This work contributes one of the most accurately reasoned studies that has appeared in connection with the geology of the Lake Superior region in some years. *Professional Paper* 144, U. S. G. S., on the Copper Deposits of Michigan, was published in 1929 by B. S. Butler, W. S. Burbank and others. This work is a deep, thoroughgoing analysis of the whole problem of the origin of the copper ores. The engineer or geologist conducting operations in either of the districts must necessarily draw heavily on the facts and conclusions developed in these two works. Whoever wishes to consider the economics of iron mining, and the problems of taxation relating thereto, will refer to the papers of Franklin Pardee of the Michigan Geological Survey and will find there remarkably clear expositions of these subjects.

In the last 10 years a valuable series of reports on the geology of the Mesabi Range and northern Minnesota in general have been issued by the Minnesota Geological Survey, reports by Grout, Broderick, Schwartz and Gruner. An interesting application of Grout's field work on this survey, as turned back to the development of the underlying theory of the whole science, may be seen in his newly published textbook, "Petrography and Petrology." This is filled with instances taken from studies made on the Duluth gabbro and the rocks of northeastern Minnesota. The whole work breathes of the field. Geologic science becomes barren, speculative and finespun, of little use for the development of our economic needs, if it cannot grow with actual field work applied in a connected manner over wide areas. Such opportunities are seldom afforded except on the work of our geological surveys. The Minnesota Survey has recently issued a geological map of the state, which is of great value to one who is called upon to pass on the mineral worth of land in a certain township.

One of the most remarkable instances of the practical application of scientific principles to the benefit of the commonwealth has been the saving of many millions of dollars in the last 15 years to the State of Wisconsin by E. F. Bean, State Geologist. This he has done by applying the principles of glacial geology, an abstruse branch of the general science, to the discovery of road-building materials, at places most convenient for their utilization in construction.

Achievements of Geological Surveys throughout the Country

Turn to any other portion of our country, the Adirondacks for example, New Jersey, Pennsylvania, the Southwest, whatever mining region you will, call upon any member of the Institute familiar with it and ask him to discuss that portion of the Geologic Map of the United

States, and he will recount an equally worthy record of the achievements of the scientific men on our geological surveys. They have played an important part throughout the whole period of the development of the mineral resources in all parts of our country, making "thousands of observations in an intentional and organized manner." By interpreting the changes in nature, the sciences pertaining to our mineral resources are evolved and then our knowledge turned to a useful purpose in the promotion of the arts and manufactures. For the most part, this work has been done by men who have "bent on study their chief care and heed," men not over desirous of this world's goods, keen to follow out their problems, made happy by a new scientific book or instrument; their chief delight, the discussion of scientific progress—"gladly would they learn and gladly teach."

Taxation of Mineral Resources

It is stated that Houghton County, in northern Michigan, in the days when the copper mines flourished paid half the taxes of the state. Possibly some statistician has calculated the amount of taxes that have been paid to the various governments, state and national, as a result of the development of our mineral resources, or the much smaller sums that have been allocated to the support of our geological surveys, but it is doubtful whether the ratio between the two sets of figures has ever been determined. As a matter of common knowledge, a very small fraction has gone to maintain the governmental institutions that have fostered the development of our mineral resources. Compared with the great material growth of the country, their share resembles the sack of oatmeal that a scholar in the old universities of Scotland brought with him in the fall for his means of living during the long winter.

Canadian Geological Surveys

At one time in the history of Canada not too far back, in the seventies, when Sir John MacDonald was Premier, there was a period of depression similar to the one that we now experience. According to Mr. John A. Dresser, who relates the story, $50,000 had been appropriated to maintain the Geological Survey of the Dominion of Canada for one of these years. During a discussion of ways and means in committee, a member of Parliament is reported to have asked what the Geological Survey was, and could not this $50,000 be cut out. "Oh, no," said Sir John, "it wouldn't do to cut that out, you know there are d—n fools who believe in that sort of thing." MacDonald is remembered today as a statesman, and this incident shows the reason. He had a breadth of view beyond the happenings of the moment, and had the courage to shape events according to his perception. It was well for Canada that there were people who believed in that sort of thing, and that Sir John knew they existed.

Those who are familiar with the development of the great Sudbury nickel district of Ontario, where the largest part of the world's nickel is produced, are aware of how important a factor in the growth of that mining industry were the reports of A. P. Coleman. These reports were contributed to the geological surveys of Ontario and Canada. The development of the noted Cobalt silver area was guided throughout its history by Willet G. Miller, Provincial Geologist of Ontario, and none were more free to acknowledge their indebtedness to him than the operators of the silver mines in that district.

It is well to recall that reports of the various geological surveys of Canada have guided the efforts of prospectors in the gold-producing areas of the Porcupine district, Kirkland Lake and Quebec areas, which in these times of stress have given Canada a favorable balance of trade when the products of the farms and forests have fallen off so greatly in value. The explorations of J. B. Tyrrell, geologist, in the northern parts of Manitoba and Saskatchewan, supplied information regarding the favorable Keewatin areas where later were found the important deposits of copper-zinc-gold ores now being worked by the Hudson Bay Mining and Smelting Co. More recently, the geological work of J. F. Wright preceded the discovery of gold ores on God's Lake in northern Manitoba. In the far off region of Great Bear Lake, the Canadian Geological Survey is supplying as rapidly as possible the topographic and geological maps that, together with the airplane, are the requisite tools of the modern explorer and prospector.

International Geological Congress and Geological Work in Russia

In the summer of 1933, the United States was the host of the International Geological Congress, the distinguished members of which came from all countries of the world. The next meeting of this body is to be held in Russia. It is of interest to know the value that Russia has placed upon geological work during the great awakening there. Hundreds of geological exploring parties have been sent in the last few years to all parts of Russia and Siberia. In the attempt to organize the life of the Russian people on a modern basis, their rulers feel keenly the lack of that systematized knowledge of their natural resources which in our own country has grown gradually, and is more or less taken for granted.

Permanent Impairment of Geological Surveys Unwise

All governmental institutions that correlate the activities of many people are seen to be cumbersome contrivances when examined critically; for example, our law courts. It would not be difficult to launch many fair criticisms against either the law courts or the geological surveys. But have any other branches of government given more value for the

expenditure? The word "survey" means literally "to see." The eye is said to be an imperfect instrument of vision, but a knowledge of its limitations makes the eyesight that we have none the less precious. The geological surveys are the organs of vision of the mining industry; admitting that in times of depression the surveys must share in the general reduction common to all, the mining industry should resist all changes that tend toward deterioration.

The disinterested scientific men who comprise the staffs of the surveys have but little aptitude for protecting their own interests. No doubt they work better when a little underfed, but it is one of the duties of members of the American Institute of Mining and Metallurgical Engineers to see that the process does not go too far. We, who have benefited so largely by their labors, should be as broad-minded as the statesman MacDonald, and protest in plain terms against false economies that threaten the permanent impairment of the geological surveys.

[For discussion of this paper, see page 452.]

Public Geological Surveys and Education

By B. S. Butler,* Member A.I.M.E.

(New York Meeting, February, 1934)

If geology is to continue to serve the mineral industry with increasing effectiveness as it has done in the past, there must be a steady output of better and better trained geologists and engineers with broader geological background. It may seem that the education and technical training of geologists belong entirely to the universities and colleges and has nothing to do with either Government surveys or the mining industry, outside of these activities furnishing a field for future work for the geological student. It will take but the most casual look, however, to see the large influence of Government surveys in education.

Geological Maps

Geological maps are essential tools in teaching geology, without which the instructor would be lost. Maps are produced by mining and oil companies, by university workers and by other individuals and institutions, but nearly all of the comprehensive maps, and most of the maps of small areas that are available, are directly or indirectly the work of public surveys. Such surveys in the past have been the only organizations with the continuity of effort and funds necessary to carry out projects that must combine the work of many individual geologists over long periods. Have we all the maps we need and of the quality we need? I believe that all who have used general maps, like the geological maps of the world, the maps of North America and the United States, maps of the several states and of smaller areas, appreciate fully the value of the maps as they are but realize also the value of greater accuracy, which can come only by more detailed work; and there are many areas of which we have no adequate maps.

Other Helps

I have chosen to emphasize maps as a help in preparing the young geologist to go out from the schools with some background of what has been accomplished and some outlook of what is yet to be done. Maps, however, are scarcely more essential to the teacher than many allied helps. What would the teacher of economic geology do if the work by Government surveys along that line were to be blotted out? We may

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think that we would have our textbooks, but a glance at any standard textbook will show how largely it has been drawn from Government reports. Oil geology has perhaps had more contributions from private surveys than most branches, yet if Government contributions were withdrawn, how great would be the loss? What would we have regarding the important subjects of utilization and conservation of soils and water, if the contribution of public surveys were removed? Certainly little enough.

In some fields that are of less obvious economic importance, yet quite as essential to the training of the well equipped geologist, the educational contribution of public surveys is quite as important. How much less would we know of petrography, mineralogy and paleontology if the direct and indirect contributions of public surveys were taken away?

Anyone who has attempted to present the subject of stratigraphy to students cannot but appreciate the unifying and steadying influence of public surveys in spite of the seeming confusion of names and correlations.

A glance over the names in the geological faculties of the universities and colleges of the country shows a surprisingly large number who have had experience and training in public surveys, and this experience is of great value to the schools and to the country in training those who must have a major part in directing the mineral industry.

No Substitute Yet for Public Survey

Are there better ways than public surveys to do geological work that requires long continued effort and long continued support? If so, they have not yet been developed and until they have been developed, support should be given to the public surveys that have served so well in the past.

[For discussion of this paper, see page 452.]

Public Geological Surveys and Geological Education

By M. N. Short*

(New York Meeting, February, 1934)

It is almost self-evident that the student of geology depends for his education in geology only in small measure upon his own observation. His chief sources of information are lectures and personal instruction from teachers, and the geological literature. Of these, the literature is by far the most important.

The total geological knowledge available to the geologist of today is substantially that which is on the printed page, and no more than that. There are many geologists of outstanding rank who during the course of a busy and useful professional career have accumulated valuable geological knowledge. This, however, is never available to the profession, owing to the disinclination of these geologists to write or to the refusal of their employers to allow the results of their work to be published. With the passing of these geologists, their accumulated knowledge is irretrievably lost.

In many mining districts the operating companies are not averse to the publication of geological information gathered by their engineering and geological staffs, but for various reasons this information is not published. However, when a public survey geologist goes into the district this information is placed at his disposal and eventually is published. But for the intervention of a disinterested public scientist, this information would have been buried in company files.

In the last analysis, the teachers themselves depend largely upon the printed page for the knowledge they pass on to the student. Without geological literature, then, the instruction of geological students would be almost impossible.

There is no question that, as a whole, geologists who are on the public payroll have to their credit far more contributions to literature than have either teachers or professional geologists, whether the latter be independent or in the employ of private corporations. The very fact that geologists are upon the public payroll places them under obligation to make available to the public the results of their endeavors. They must either prepare these results for publication or they must furnish data or otherwise aid their colleagues to publish their results. The success or failure of a public geological survey depends entirely on the

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caliber of its publications. Likewise the success or failure of a geologist in a public geological survey depends entirely on his printed contributions. The teacher prepares articles for publication if his inclination urges him to do so and if his ability permits, but his output is restricted by the fact that he must do this work at intervals between his necessary teaching hours. Many teachers have an academic schedule so heavy that they have no time to write, much as they may desire to do so. The professional geologist, as a rule, is under no obligation to write for the public and is often prohibited or restricted by the confidential character of his work.

TABLE 1.—*References and Illustrations in Textbooks*[a]

Textbooks	References			Illustrations		
	From U.S.G.S.	From State Surveys	From Others	From U.S.G.S.	From State Surveys	From Others
General Geology						
Longwell, Knopf and Flint....	6	2	72	50	7	294
Emmons, Thiel, Stauffer and Allison....................	31	2	151	57	7	386
Scott......................	22	4	264	66	11	319
Economic Geology						
Lindgren....................	552	95	1890	117	9	207
Emmons....................	556	83	600	75	4	125
Ries........................	838	462	1496	120	37	257

[a] As an indication of the extent to which information from public surveys is used in geological magazines, the 1932 bound volume of *Economic Geology* was consulted. The references cited in the articles therein were as follows: U.S.G.S. 110, state surveys 13, others 587.

It is difficult to gage the relative importance of public geological surveys in the contributions of geologic literature useful to the student of geology. One method is to determine the relative importance of contributions from public geological surveys to the total in textbooks used by the student, and this is done here. The state geological surveys do not appear in their true importance in such a compilation. Their work is largely limited to local problems, and rightly so. For instance, the State Geological Survey of Pennsylvania is chiefly concerned with coal and other resources of that state, and extracts from its publications would not be found in textbooks to the same extent as those from publications of an organization of more diversified interest and application.

There is no question that the United States Geological Survey is and always has been the most important source of geological knowledge for the nation. It constitutes the largest and in many respects the most able group of geologists found in any one organization. In the

compilation in Table 1, only articles published by that Survey itself are cited. This by no means represents the total contributions to geologic literature from geologists of the Survey. The facilities of the Government Printing Office and the appropriations for printing are cramped to an extent that cannot be appreciated by one outside of that organization. Therefore geologists of the Survey are encouraged to publish their results elsewhere, and they are to be found in every geological magazine. Likewise, in many cooperative projects of the United States Geological Survey, the results appear under state auspices and at state expense. But even these do not constitute the sum total of the contributions to geological literature of this magnificent organization. One need but look through articles published on regional or economic geology by American writers outside of that Survey to be convinced that most of these articles have references to or information derived from Survey writings.

Of more than usual interest is the extent of participation of public survey geologists in ORE DEPOSITS OF THE WESTERN STATES (Lindgren Volume), published by the American Institute of Mining and Metallurgical Engineers in 1933. Of the authors who contributed articles to that volume, 27 are present or former members of the U.S.G.S., 2 are from state surveys, 2 are from the Carnegie Institution, and 13 are not connected with these organizations.

[For discussion of this paper, see page 452.]

Value of a State Geological Survey to a Nonmining Community

By William M. Agar,* Associate Member A.I.M.E.

(New York Meeting, February, 1934)

Now that both the national and state legislatures are seeking ways of reducing expenses, the appropriations for geological investigation and for the study of mineral resources have been greatly reduced and in some cases entirely stopped. Is this policy justified? The sums saved by these reductions are always small. If the work accomplished by these surveys has no intrinsic value to the community, but is only an interesting way of spending some of the people's money when that money is plentiful, there should be no surveys at any time. If, on the other hand, they perform a necessary function, it is indeed foolish and short-sighted to save these paltry sums to the detriment of the community.

It is not my purpose to undertake a general justification of geological surveys. Rather, I wish to call attention to the work of one state survey that has been discontinued, and to indicate ways in which the work was valuable to the people, even though that state's mineral resources are not very important, and why it should be continued.

Though at one time in Connecticut's history iron mining and smelting were important, and copper was mined in appreciable quantities in two localities, it is many years since it could be regarded as a mining state. At present Connecticut stands far down among the states in the value of its mineral products. Granite for architectural and structural purposes, trap rock, clay, agricultural lime, feldspar and quartz, together with a few other nonmetallic minerals, are produced in appreciable quantities, but the natural resources of the state consist at present much more largely in its attractive scenery, woods, lakes, shore line, and in the opportunities that these offer for rest and recreation.

Is the prosecution of geological work in such a state a waste of the taxpayer's money? Or can it be that though it was formerly valuable, the work is now completed? The only way to answer these questions is to review the geological work done in the past and to consider the type of information the people want, as reflected in the requests that have been received by the director of the survey in the last few years.

There have been two periods during which Connecticut has supported geological work within its borders. The first began in 1835 when Percival

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and Shepard were appointed to make a geological and mineralogical survey of the state, and ceased in 1842 when Percival handed in his report. The second period commenced in 1903, when the Geological and Natural History Survey was established. Only a part of the work done by this survey was geological in its nature.

Between those two dates much geological work was done, both by individuals, chief among whom was James D. Dana, and by the United States Geological Survey. W. M. Davis, Raphael Pumpelly, C. R. Van Hise and W. H. Hobbs are a few of those who worked for the Federal survey within the borders of Connecticut.

Slowly, however, the need for a systematic examination of the geology of the state became apparent as demands for information continued to come from individuals as well as from educational institutions. When the survey of 1903 was established it published the Bulletin of the Geology of Connecticut, the Preliminary Geological Map of Connecticut, the Lithology of Connecticut, accompanied by a collection of typical Connecticut rocks, and a number of other papers of importance. These publications were all excellent and the demand for them was great, but they have all been out of print for many years and are now available only in libraries. They were, however, very decidedly "preliminary" publications, and it was intended that they should be superseded by more thorough compilations.

Shortly after this period of early activity, more fundamental studies were undertaken. Some have been completed, others have been stopped by the cessation of appropriations. Bulletins on the glacial geology and mineral localities of Connecticut have appeared and a number of other local studies have been completed and published, but the contemplated new Bulletin of the Geology of Connecticut and the new map are not yet finished.

There is now a continuous demand for information concerning the bedrock geology of many localities and for geological maps of the state or of parts of it, but there are no state publications available to satisfy these demands, though the material was being collected when the survey was stopped. Requests for general information concerning Connecticut minerals are the commonest of all. Happily there is a recently published bulletin that satisfies most of these demands, though it is not detailed enough to satisfy all. Requests for samples of certain rock formations and typical minerals, or for sets illustrating Connecticut rocks for teaching and exhibition purposes are fairly common. These are demands that the survey can supply when it is in existence. There is then an evident demand for detailed geological and mineralogical information from the schools and from individuals which, in most cases, can now be met only by reference to obsolete state publications available in a few libraries.

There is another way in which the information obtainable by the survey is valuable. It would be foolish to pretend that a new, detailed survey would uncover hitherto unknown mineral resources. The most that can be said is that technological advances often render minerals valuable that previously have been of no use, and that it is a sound economic policy to have as complete a knowledge of the rocks and minerals within state boundaries as can be obtained. The people of the state, however, demand mineralogic and geologic information of many kinds. Requests for information on the occurrence of beryl, andalusite, sillimanite and cyanite in Connecticut have all come in in recent years. The state survey has already accumulated sufficient information to be pretty certain that no valuable deposits exist, though all of those minerals occur in some quantity.

Clay, marl, molding sand, diatomaceous earth, peat, mica, feldspar and topaz are some of the minerals that occur in the state which have been inquired about. Silver, copper and tungsten were formerly mined in small quantities and are subjects of inquiry. Ocher, slate, asbestos, manganese, tin, scandium, bismuth and diamonds are either unimportant or absent, but all have been inquired about, and samples of rocks and minerals frequently are sent in to be determined.

These various inquiries come from people who are landowners and taxpayers and have a right to expect information. Often the information is purely negative; that is, it is the denial of the existence of known deposits of this or that, or it is the assurance that certain deposits are worked out or have no intrinsic value, but it is important nevertheless. Three years ago a certain individual conceived the idea of helping the farmers to get work and reviving industry by opening up some of the old iron mines in Kent and Salisbury. These have long been abandoned and flooded, and were mostly nearly exhausted. The nickeliferous pyrrhotite in the basic intrusions near Litchfield and Torrington are recurrently a near source of ill-advised "booms." It is important to have some source of information to which all such questions can be referred.

There is still another general way in which a well established survey whose work is known to the people can be valuable. Geological information is often sought in connection with tunneling, road building, quarrying, harbor protection, and in many other engineering operations. Often it is not obtained when it should be, and the blame for this attaches as much to the survey as to the people, since the existence of a survey is unknown to many. In fact, a fair proportion of the inquiries previously mentioned are sent to the Governor's office and thence to the proper source. There should be some way in which the availability of information, once it is collected, is made known to the public.

There are many ways then in which a geological survey can be useful to the citizens of a state, but one should not attempt to measure its

value in dollars and cents alone. It has or it has not a place in the life of a community, depending upon the intelligence and foresight of the people. Its immediate cash value may be small; its cash value in the future is always problematic, though potentially large; its educational value is perhaps the greatest of all. This review of the demands for information made upon the survey shows that there is sufficient reason for its continuance from the educational side alone. Therein lies its justification. It should aim to furnish understandable dissertations on the rocks, minerals and geological history of the state; as well as maps, specimens and more detailed information to those who desire it. The more continuous the support of the state, the more fully will this be accomplished and the more the ways that will be found to make it of practical value.

[For discussion of this paper, see page 452.]

Discussion on Relations between Government Surveys and the Mining Industry

[Refers to papers that appear on pages 393 to 451, inclusive.]

(*Joseph T. Singewald, Jr. presiding*)

G. F. Loughlin,* Washington, D. C.—With reference to Mr. Bain's paper: The scarcity of adequate geologic data on building stone reflects, among other things, a lack of interest on the part of geologists. It has been one of my duties to attend to matters relating to building stone and other structural materials that have come to the U. S. Geological Survey, but for several years my principal administrative and other duties in the Section of Metalliferous Deposits have prevented me from giving structural materials the attention that they deserve. I have felt that investigations relating to structural materials should be assigned to someone else, but thus far nobody with a sufficient interest in the subject has come forward; further, the specific calls for these investigations have been so few and far between that it has not seemed practical to draft any one for the job. The general situation is such that steady and substantial progress in the application of geology to the utilization of structural materials is not likely to be made unless someone with keen interest in the subject takes the initiative. If the start is once made, I know from experience that cooperation from the more progressive members of the quarry and-building industries will be readily forthcoming.

Mr. Sales' suggestions are all constructive and most welcome. A thorough, detailed discussion of them might be as long as his manuscript, but could largely be summarized with the one word "amen" qualified by the alibi that a chronic shortage of funds and therefore of personnel has prevented us from carrying out some of his suggestions already. A few of them might call for an Act of Congress before we could undertake them, and one or two, such as the preservation of mine maps, with which I heartily agree, would call for much additional space as well as clerical and supervising help. Several items in Mr. Sales' paper—for example, the question of balance between the scientific and more directly practical studies and the surveys or resurveys of the larger and smaller mining districts—have been covered in my contribution to the symposium.

The suggestion of frequent reviews of progress in the study of ore deposits is excellent and can be followed without serious diversion from projects already on the Survey's program. Brief reviews by Survey men have been published in periodicals, and the contributions by several of them to the Lindgren Volume[1] may also be cited as serving this purpose to some degree. The practice of publishing short papers by Survey men in outside journals rather than in Government reports is largely the result of experience and expedience. Our printing funds are limited, and considerable time must elapse between the transmittal of a paper and its publication. Time is saved therefore by sending papers to outside journals, and the editors of those journals are usually glad to receive them. Members of the Survey would doubtless prefer to have the products and byproducts of their official work appear in official Survey publications if conditions were more favorable.

If we were left entirely to ourselves the balance between the more scientific and the more directly practical studies would be somewhat better than it is, but the

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[1] Ore Deposits of the Western States (Lindgren Volume). A.I.M.E., 1933.

demands on us are so many and various that any one of us is extremely lucky if he can finish one job before he has to be assigned to another. Aid to the prospector has been given whenever opportunity has permitted, but has been mainly incidental to other work and has not been so widely recognized. To organize a section especially devoted to such aid would require a substantial addition of experienced men to our force or a drastic inroad on our already too small force of men who are carrying on the scientific and directly practical studies.

The scarcity of our publications concerning recent developments in the major districts reflects not so much a lack of interest in those districts as an insufficiency of personnel to meet this and other demands. Geologists in the Survey's section of mining geology are imbued primarily with a love of the science of ore deposits and would all welcome opportunities to keep up with the developments in each of the major districts, but if they were to do so our force would have to be doubled or practically all other work would have to be abandoned. A few of us are keeping in touch with major districts in which we have worked, but cannot always find the time for the resurveys that the districts deserve. Some of the districts mentioned by Mr. Sales are now, or recently have been, the subjects of restudy, and we wish that they all were.

The soundness of the suggestion that broad general studies be based on geologic rather than geographic units is obvious. The Survey is represented on most if not all of the geologic committees of the National Research Council and aims to make appropriate use of any advances in the broader as well as the more restricted problems of geology. The geologic unit has been kept in mind even though conditions governing the preparation of reports have called for a geographic limit to the ground covered, or the title of the paper has a geographic meaning; for example, Lovering's paper on ore deposits in the Front Range of Colorado, and Burbank's on vein systems of the Arrastre Basin and regional structure in the Silverton and Telluride quadrangles, Colorado, are both based on geologic units. There are several geologic units in Colorado that are individually or mutually involved in the control of ore deposits and they are all to receive attention in the course of our cooperative program in the state. We hope that eventually all will be treated. As stated in my own paper, no one can conduct a study of a single district or closely spaced group of districts without realizing the need of a thorough acquaintance with the regional geologic unit within which the districts lie. C. P. Ross' *Professional Paper* on South Central Idaho, now essentially completed, is mainly founded on geologic units, the Idaho batholith and the system of younger Tertiary intrusives, together with overlapping parts of structural units that extend beyond the limits of the state. These units, as they affect the same territory, are best treated in the same report, but they are so extensive that the time necessary to cover them completely would greatly defer the publication of valuable material and would be beyond the scope of the cooperative program now under way in Idaho. Treatment of the Idaho batholith as a whole would be an appropriate sequel, but the three parties that are now working on metalliferous deposits in Idaho are kept busy trying to meet the demands of the cooperating agency, the State Bureau of Mines and Geology, for intensive studies of comparatively local problems. Such local problems contribute, whether limited by geographic or geologic features, towards the study of large geologic units, and in turn are more readily solved if a fair knowledge of the major unit is already available. It is a poor rule that does not work both ways.

Delay in the examination of new discoveries is regretted, but may be attributed to the chronic shortage of funds and personnel. Plans for the study of new discoveries have had to be deferred repeatedly, especially during the last few years. Sometimes a topographic base map that has been ordered for the work is promptly completed, but has to remain unused until funds for the geologic work become available.

Delay in the publication of reports is deplored, but to a great extent it is unavoidable. I need not dwell on delays that arise after a report leaves the Survey, as there

are other delays nearer home. Some noncooperative reports may have to give priority to cooperative reports on work that has been partly paid for by the cooperating agencies, but reports of economic bearing, even though noncooperative, are given general priority. Delays are especially irksome to the author, but the snags that he strikes in the preparation of a report on a complex mining district are many and the time required to digest and coordinate the data obtained in a single field season, to say nothing of two or three seasons in one district, is invariably greater than even the oldest and ablest authors estimate. B. S. Butler, who has never allowed grass to grow under his feet and whose work speaks for itself, has suggested the following formula for estimating the office work on a report: "Double the time you think it will take and then add 20 per cent." There is a big difference between the preparation of a commercial report for a single company and that of a Survey report that must adequately cover the geology of an entire district and serve as a reference to the general public for years. Survey men have prepared reports equivalent to commercial reports either while in the field or within a minimum of time after return to the office. If anyone thinks that a comprehensive report like one of our professional papers can be written rapidly, he should try writing one himself, then have it criticized by his friends who are specialists on the different subjects involved, and then revise it in accordance with their suggestions. Attempts at short cuts are likely to mean extra work in the end. Parts of the text may be condensed eventually, but the amount of labor involved in preparation of a condensed, concise text is greater than in that of a hastily written verbose text. After the text of his report is in acceptable form, the author will find that considerable additional time will be necessary for draftsmen to put his maps and other illustrations in presentable form for publication. When his report is finally ready for the printer, it may have to wait a few months or even a year or more until funds become available for printing it and the other equally or more important reports already completed.

The distribution of its reports is something over which the Survey now has less control than formerly. About five years ago, on the urging of a Committee of Congress and the Bureau of the Budget, distribution was placed on a sale basis. The Survey's own editions are now sufficient only for immediate official purposes, including library exchange sendings and small reserve stocks for official and special uses. The entire cost of these editions, including the setting of type for the texts and the preparation of plates for maps and other illustrations, is borne by the Survey's publication funds. With an urgent list of reports awaiting publication, it does not seem feasible to divert part of those very limited funds to the reprinting of the many older reports which, though out of print, are at least available to the public through consultation in many libraries. Indeed, the pressure to make available the information in reports not yet issued has, in recent years, led to the doubtful economy of foregoing the expense of electrotyping the texts so that they can be reprinted if desirable.

The editions for sale by the Superintendent of Documents are ordered by him in numbers based on the experience with sales under the present plan, and are paid for by his revolving fund. To avoid tying up that fund as a "frozen asset," and because he has a serious problem of storage space for the many documents issued by the several Federal departments, his tendency is to order only enough for a few years, rather than a sufficient number to supply the smaller continuing demand of later years. The Survey has no control over those printed for sale; in fact, at the end of the fiscal year after the year of publication it is required to turn over to the Superintendent any remaining copies of its own supply, except a few retained for anticipated official use.

With reference to extra copies of maps from reports, some improvement is being made, though not as much as could be accomplished with more adequate funds. For

several years, when maps to accompany reports have been printed in the Survey's own engraving plant, overruns of maps most likely to be required separately have been printed and held by the Survey for future needs. At this time, arrangements are being made to obtain similar small overruns when the maps for reports are printed by commercial plants under contract with the Public Printer.

Overlap between the state and Federal surveys is rarely serious. The Federal survey has plenty to do without encroaching on the fields or programs of the state surveys, and Federal projects within states that maintain surveys are usually undertaken either at the request of the state survey, or after consultation with it. The publication of cooperative reports by the state surveys or by such organizations as the Colorado Scientific Society may scatter the centers of distribution but it has the advantage of a larger aggregate printing fund and more prompt publication.

Preliminary reports are issued whenever feasible, with the intention of releasing information of practical importance without waiting for completion of the entire complex report. Papers published by the Colorado Scientific Society and bulletins issued by the state bureaus of Idaho and Nevada are outstanding examples of recent preliminary publications. One difficulty with a preliminary report or abstract is that the author may not know just what he wants to say until he has finished the complete report, but the preliminary reports just cited are sufficiently numerous to show that we try to get the information out as promptly as good work permits, and we are not afraid to make any revisions that may be necessary later. Even a good preliminary report, however, requires an appreciable amount of time for its preparation.

To aid in the distribution of reports the Survey has for the last 30 years or more maintained distribution offices in Denver, Salt Lake City, San Francisco, and Los Angeles, as well as at the office of the Alaska Railroad at Anchorage, at the Alaska Agricultural College and School of Mines, College, Alaska, and at the office of B. D. Stewart, Supervising Mining Engineer, Juneau. Reports and maps of local interest are kept in stock as long as available and are always on file for consultation. Most of our state index maps, which are accompanied by lists of reports referring to the respective states, also list from 5 to 20 dealers that sell topographic maps. We are eager to make our publications readily available and are glad to take any step to do so in accordance with regulations.

The foregoing comments show that the Survey's point of view is in general accord with that expressed by Mr. Sales and doubtless held by many others. There is always danger, however, that an internal viewpoint may become warped, and we are indebted to Mr. Sales for giving us this chance to see ourselves as others see us. Such opportunities are stimulating and we hope the Survey's relation to the mineral industry will be reviewed again from time to time. Our shortcomings appear to be not so much what we do as what we don't do but would if we could. The diversity of demands on us and the limitations of our organization prevent us from going as far as we would like in any of our activities. This diversity is a further disadvantage in that the beneficiaries of different branches of our work have so little interest in common. Metal mining, coal mining, oil production, stone quarrying, miscellaneous nonmetallic mineral production, education, and general popular interest have too many troubles of their own and too few interests in common to lead them to think of uniting in the support of such a mutually beneficial organization as the Geological Survey, but if a more unified support were to develop the Survey would have a correspondingly greater chance to meet the demands of each of the interested industries.

G. O. Smith, Washington, D. C.—May I add my amen to Mr. Loughlin's remarks about the U.S. Geological Survey? Our critic has been gentle in his criticism, and I cannot add to the alibis already presented to excuse the Survey. I am no longer under any compulsion to defend the Survey, being now a rank outsider, so my words may be taken as the comment of one on the outside looking in.

The underlying policy of the Survey has been to conduct it so as to aid its important clients, the mining engineers and the mining industries. I know the leaders of the mining industries, and can say they are in accord with the policies outlined by Mr. Sales.

In the matter of publication, the chief of the Survey has two problems, the author and the printer. Sometimes the author is the more difficult of the two and is responsible for holding up the report. I recall one case in which two Senators brought charges against the Director of the Survey to the effect that he was holding back an important report. This was about like accusing a farmer of holding back the oxen he was goading to move on.

Even after the author has responded, and the manuscript is ready, there is the Public Printer. The speeches of Congressmen have the right of way. That is as it should be, because it is only then, if ever, that such speeches have any value. But after the printer does get around to our report, the difficulty of reproducing colored maps delays the work. With regard to the size of the edition, it is necessary to strike a happy medium, between one quickly exhausted and one that clutters up the shelves for years. Every manuscript report, when ready for the printer, has a slip attached reviewing the history of the publication of previous similar reports, together with the recommendations from the author and the officials of the Survey as to size of edition. Nevertheless, it shocks me to look back and see how many times the editions were much too large or much too small.

With regard to issuing a surplus of maps, the printer has complained that he has no authority to print more copies of maps than needed to bind in reports, but large overruns have sometimes been used to take care of that.

When in charge of the Survey, I was in favor of the re-survey of old regions. I agreed that my own work in the Tintic should be reviewed by Loughlin, as an evidence of good faith. It proved an eye-opener to me to see how standards of work had improved in 14 years. So also in a visit to Butte recently I went underground, and realized how much more service mining geologists can give both to the operators and to the students of ore deposits than in former years.

With regard to keeping mining records, I was impressed several years ago, when visiting the very efficient state survey of Illinois, with the completeness of its well records. For the Federal Survey to carry out a similar program would require the capacity of a Hall of Records; so it does not seem practicable to keep all the records we should like to.

The Survey geologist who has any confidential records entrusted to him is really a trustee and faced with a problem. Years ago a coal operator turned over to me all his records, which were of inestimable value to me in my geological studies. When the work was finished, I returned or destroyed the records, I forget just which, because I was unwilling to take the responsibility of keeping these confidential records in a public office. It is of the highest importance that the Survey keep faith in this way with the mining industry. That it does so is shown by an incident that pleased me greatly, when the president of an oil company against which the Government had a suit consented to the use of the company's confidential records by the U. S. Geological Survey in connection with some of its investigations.

S. F. Kelly,* New York, N. Y.—I should like to refer to Mr. Bain's remark regarding the little knowledge of building stones possessed by those most interested in using these materials. Recently I collaborated with another man on the idea of writing an article, more or less popular, about the geological origins of building stones, and the correlation between geological and mineralogical characteristics of ornamental stones and their engineering and architectural qualities. It was our idea to emphasize

* Consulting Geologist and Geophysicist.

the geological side, so as to give the architects and engineers some idea of where their building materials came from, and how they were formed. We interviewed the editor of one of the larger architectural magazines, who told us flatly that his readers would not be interested in that phase of the subject. This impels me to the belief that what the geological and mining professions need is a good publicity agent, or to put it less crudely, a "public relations counsel," to tell not only the architects but the public in general how much there is of interest in geology.

To the average layman, dirt is dirt and "rocks is rocks"; he knows little of geologists and less of geology, and buzzes through the countryside with unseeing eyes. The expenditure of effort in the right direction should create as much public interest in the fascination of the rocks and hills as has been achieved by the spectacular developments in astronomy and physics. But it needs good publicity managing. Why should not the various geological and engineering societies and organizations cooperate along these lines?

(*Alan M. Bateman presiding*)

A. M. Bateman,* New Haven, Conn.—I also wish to add a word of appreciation and to express gratitude to the group that contributed to this symposium and discussion. Especially, I wish to congratulate Mr. Sales for his constructive paper and to echo his suggestion of the benefit to be derived from a concentrated study of geologic units rather than individual map areas. The Boulder batholith is one such geologic unit, and the work on the Bushveld igneous complex in South Africa shows the advantages of studying this amazing field as a single geologic unit that illustrates unusual magmatic differentiation and the formation of platinum, magnetite, chromite, nickel, and other mineral deposits. I believe we could with advantage follow this procedure more than has been done in the past.

With reference to Mr. Loughlin's string of alibis, the lack of funds is a sad commentary on the present situation of Federal geologic work. It is a situation that is partly our own fault. The blame must rest on us that the needs of the Survey are not properly understood and that the value of its work is not properly appreciated. It is indeed unfortunate that the Survey has to plead a lack of funds for carrying on work that is so essential to the understanding of the mineral resources of our country. Such funds are voted by Congress, and if they have cut the appropriations more than is justified by the present need for Government economy, and relatively more than in other Government branches, it is because our Congressmen and Senators do not realize the value of this work. Therefore each of us can help by writing to his Congressmen and Senators urging adequate support for the Government Surveys in order that they may perform the work so necessary to the mineral industry. Few Congressmen realize, perhaps, that the mineral industry is second in importance only to agriculture.

G. C. Branner,† Little Rock, Ark.—The expansion of state surveys is shown by the fact that in 1900 there were 16 active state surveys while in 1930 41 states had geological surveys. In 1900 $141,000 was the total annual appropriation for these surveys, while in the years 1928 to 1932 the total annual appropriation was either slightly less or more than one million dollars.

I agree with Professor Bain and Professor Bateman that we must impress on the legislators the value to the public of the geological surveys, and should point out that the work they do perform is such as to increase property values and thereby increase

* Professor of Economic Geology, Yale University.

† State Geologist, Arkansas Geological Survey.

property and corporation taxes, and create and increase the payrolls in the communities they serve.

S. St. Clair,* New York, N. Y.—I cannot refrain from saying a word of appreciation of the work of the United States Geological Survey. I was a member of that organization some years ago and I set for myself the task of reviewing a large part of its published literature, especially the economic papers. I was amazed at the amount of specific information that could be obtained from the Survey reports. I know of no better post-graduate course for the young graduate of today.

Much of the criticism which has been offered here I am sure is meant to be constructive. Probably the most glaring shortcoming of the United States Geological Survey is the tardiness in getting to the public the findings of its economic geologists.

The Survey fills a scientific and economic position unique in its value to industries dealing with natural resources, and I hope to see it function in the future under no curtailing handicaps.

D. H. McLaughlin,† Cambridge, Mass.—I would like to see the annual review of geological progress, already suggested, made more extensive than indicated. Very little is published about the ideas developed in the course of operating geologic work in mining camps. Excellent geology is being done in connection with such work, and company geologists as a rule are not at liberty to publish their results. It would be very much worth while to get more of them into print, and possibly cooperation with the Survey in an annual summary would be helpful in this respect.

As a member of the geological profession who has had no connection with the Survey at any time, I should like to express my appreciation and admiration of the splendid work that its members have done and are doing in spite of present handicaps.

C. Zapffe,‡ Brainerd, Minn.—I am not on a survey and I am not even a geologist on the staff of the company that employs me, but I am, nevertheless, interested in the subject.

In the days when I graduated from college, the graduate had a job waiting for him on the Federal Survey. Occasionally a state survey provided a place but only rarely did industry provide one. If the latter did, the individual taking the job was looked upon as a freak and what he said was scoffed at. Nowadays the situation is that industry provides most of the jobs, state surveys do better than before and in the Federal Survey the chances are almost nil. If something is to be done about the Federal Survey, let us analyze things from this reversed standpoint and see first what the geologist in the industry needs and can do and next what a state survey is permitted to do, and then fit the Federal Survey to that form.

A geologist in industry has an unlimited working field. Usually he is handicapped because he does not have libraries or ready access to fine public scientific libraries. Often he is not allowed to publish articles, but some nonaffiliated body is permitted to do it. These gaps must be filled by somebody or something. Do not let us think of geologists in industry having a department such as Mr. Sales enjoys. His is a rare case.

State surveys are as different as the states themselves. All and everything is limited to state boundaries, regardless of all else. Problems differ in each state and some are not even geological problems. The survey must justify itself to the citizens, who care not a bit about scientific controversies but levy taxes to maintain a survey to have its help in creating more taxable property. When the survey ceases to be

* Consulting Geologist.

† Professor of Mining Engineering, Harvard University.

‡ Manager, Iron Ore Properties, Northern Pacific Railway Co.

able to show a legislature that such can be and is being achieved, the survey is apt to cease to exist promptly. In our state the large iron-mining industry gets no help through the state survey; it gets help through a special appropriation for an experiment station. Our state survey cannot give help because it is more like summer employment for a few men of the State University than a continuous all-year department.

Consequently, we shall always have to look to the Federal Survey to do work take industries and states do not do. Let the Survey follow on this trail rather than that full control and all leadership as in the past. Times have changed things and the day comes when we must change established practices and, perhaps, shift positions. The Federal Survey can always have a place anywhere working out fundamental problems. To industry, as Mr. Sales suggests, keeping up publishing current progress is very important. I think it is the most important thing. It irks me that some survey publications have been kept unmodified. Small treatises or presentations have become more important than momental publications.

State or Federal, to maintain the surveys the taxpayer must be sold on it and the legislators convinced. If such departments are now in the doldrums, it is because they have outlived their usefulness or have fallen asleep in quiet content.

W. F. Pond,* Nashville, Tenn.—I looked forward to getting from this symposium a broad indication of what the industry hopes to get from state and Federal surveys. I conclude that either we are not as valuable as we think we are, or are not doing the kind of work we should, or are not getting the people to realize the value of our work. We know its value, but the people and the legislators do not, and it should be placed before them. It may be that the fundamental reason for our not getting the support we should lies in our not making known the value of what we do.

I wonder if some strong committee from the industry could not formulate a paper setting forth what is expected of the surveys, for we really need some expression from that quarter of what is wanted of us.

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* State Geologist, Tennessee Division of Geology.

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(Note: In this index the names of authors of papers and discussions and of men referred to are printed in small capitals, and the title of papers in *italics*.)

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